US012238069B2

(12) **United States Patent**
Kommula et al.

(10) **Patent No.: US 12,238,069 B2**
(45) **Date of Patent: Feb. 25, 2025**

(54) **SELF-CORRECTING SERVICE LEVEL AGREEMENT ENFORCER**

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(72) Inventors: **Raja Kommula**, Cupertino, CA (US); **Rahul Gupta**, Kanpur (IN); **Ganesh Byagoti Matad Sunkada**, Bengaluru (IN); **Tarun Banka**, Milpitas, CA (US); **Thayumanavan Sridhar**, Sunnyvale, CA (US); **Raj Yavatkar**, Los Gatos, CA (US)

(73) Assignee: **Juniper Networks, Inc.**, Sunnyvale, CA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **18/472,111**

(22) Filed: **Sep. 21, 2023**

(65) **Prior Publication Data**

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(30) **Foreign Application Priority Data**

Nov. 30, 2022 (IN) 202241069004

(51) **Int. Cl.**
H04L 9/40 (2022.01)
G06N 5/022 (2023.01)
(Continued)

(52) **U.S. Cl.**
CPC .... ***H04L 63/0263*** (2013.01); ***G06N 5/022*** (2013.01); ***G06N 20/20*** (2019.01); (Continued)

(58) **Field of Classification Search**
CPC H04L 41/5009; H04L 43/0811; H04L 43/0888
See application file for complete search history.

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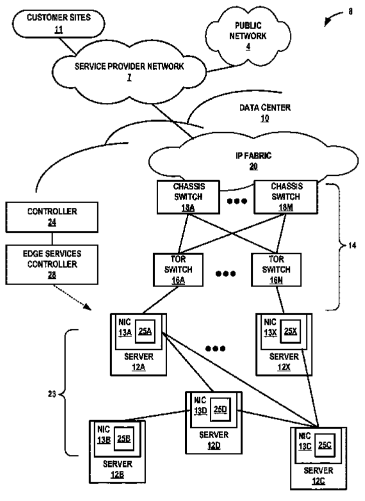
(74) *Attorney, Agent, or Firm* — Shumaker & Sieffert, P.A.

(57) **ABSTRACT**

Example systems, methods, and storage media are described. An example network system includes processing circuitry and one or more memories coupled to the processing circuitry. The one or more memories are configured to store instructions which, when executed by the processing circuitry, cause the network system to obtain telemetry data. The instructions cause the network system to determine, based on the telemetry data, that an application running on server processing circuitry does not meet at least one service level agreement (SLA) requirement, the server processing circuitry not including processing circuitry resident on a network interface card (NIC). The instructions cause the network system to, based on the application not meeting the at least one SLA requirement, determine to offload at least one component of the application from the server processing circuitry to the processing circuitry resident on the NIC.

18 Claims, 31 Drawing Sheets



(51) **Int. Cl.**

G06N 20/20	(2019.01)
H04L 41/14	(2022.01)
H04L 41/16	(2022.01)
H04L 41/5009	(2022.01)
H04L 43/0811	(2022.01)
H04L 43/0888	(2022.01)

(52) **U.S. Cl.**
CPC ***H04L 41/14*** (2013.01); ***H04L 41/16*** (2013.01); ***H04L 41/5009*** (2013.01); ***H04L 43/0811*** (2013.01); ***H04L 43/0888*** (2013.01); ***H04L 63/0236*** (2013.01); ***H04L 63/0245*** (2013.01); ***H04L 63/1416*** (2013.01)

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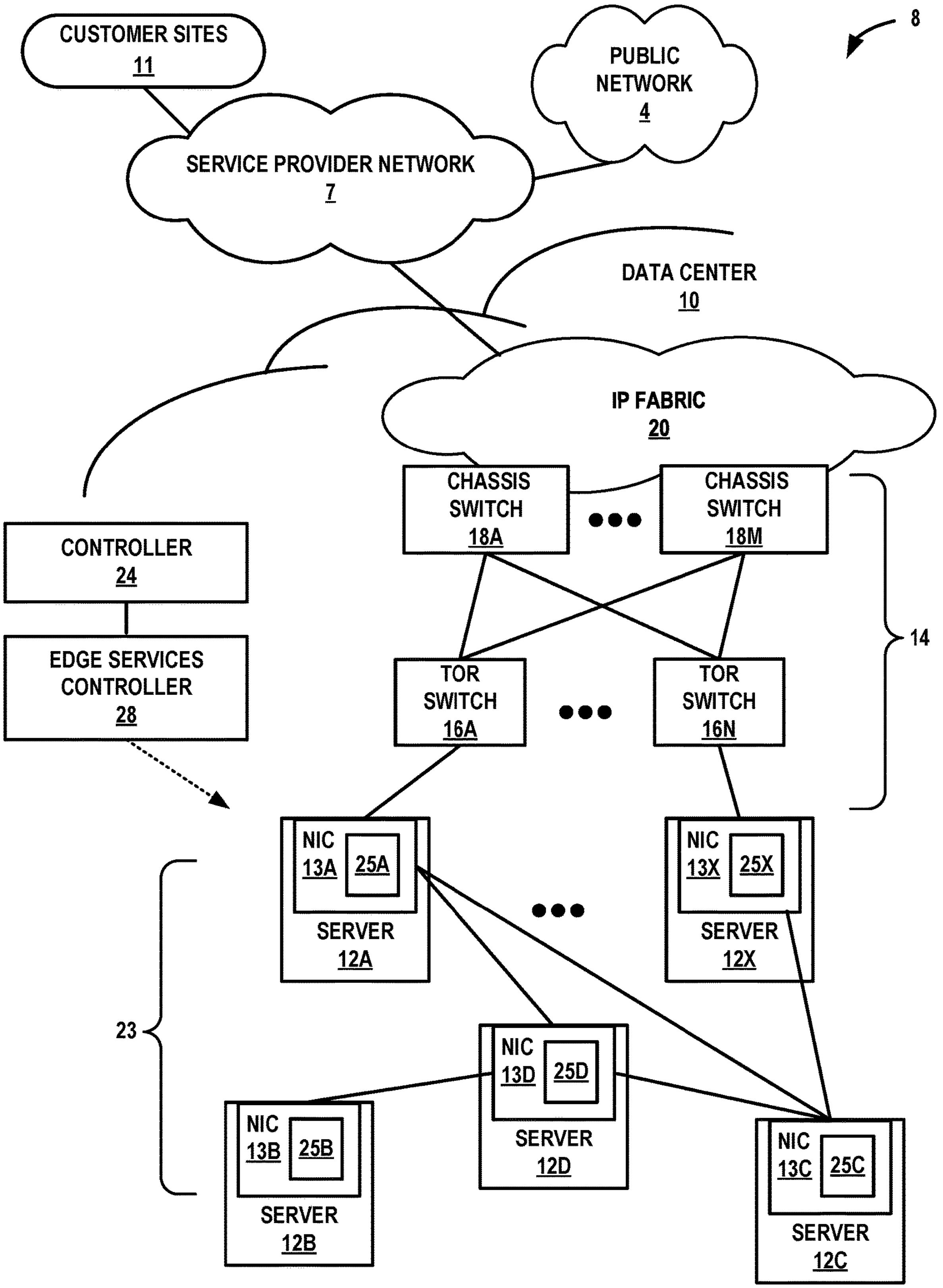
8
CUSTOMER SITES 11
PUBLIC NETWORK 4
SERVICE PROVIDER NETWORK 7
DATA CENTER 10
IP FABRIC 20
CHASSIS SWITCH 18A
CHASSIS SWITCH 18M
CONTROLLER 24
EDGE SERVICES CONTROLLER 28
TOR SWITCH 16A
TOR SWITCH 16N
14
NIC 13A
25A
SERVER 12A
NIC 13X
25X
SERVER 12X
23
NIC 13D
25D
SERVER 12D
NIC 13B
25B
SERVER 12B
NIC 13C
25C
SERVER 12C

FIG. 1

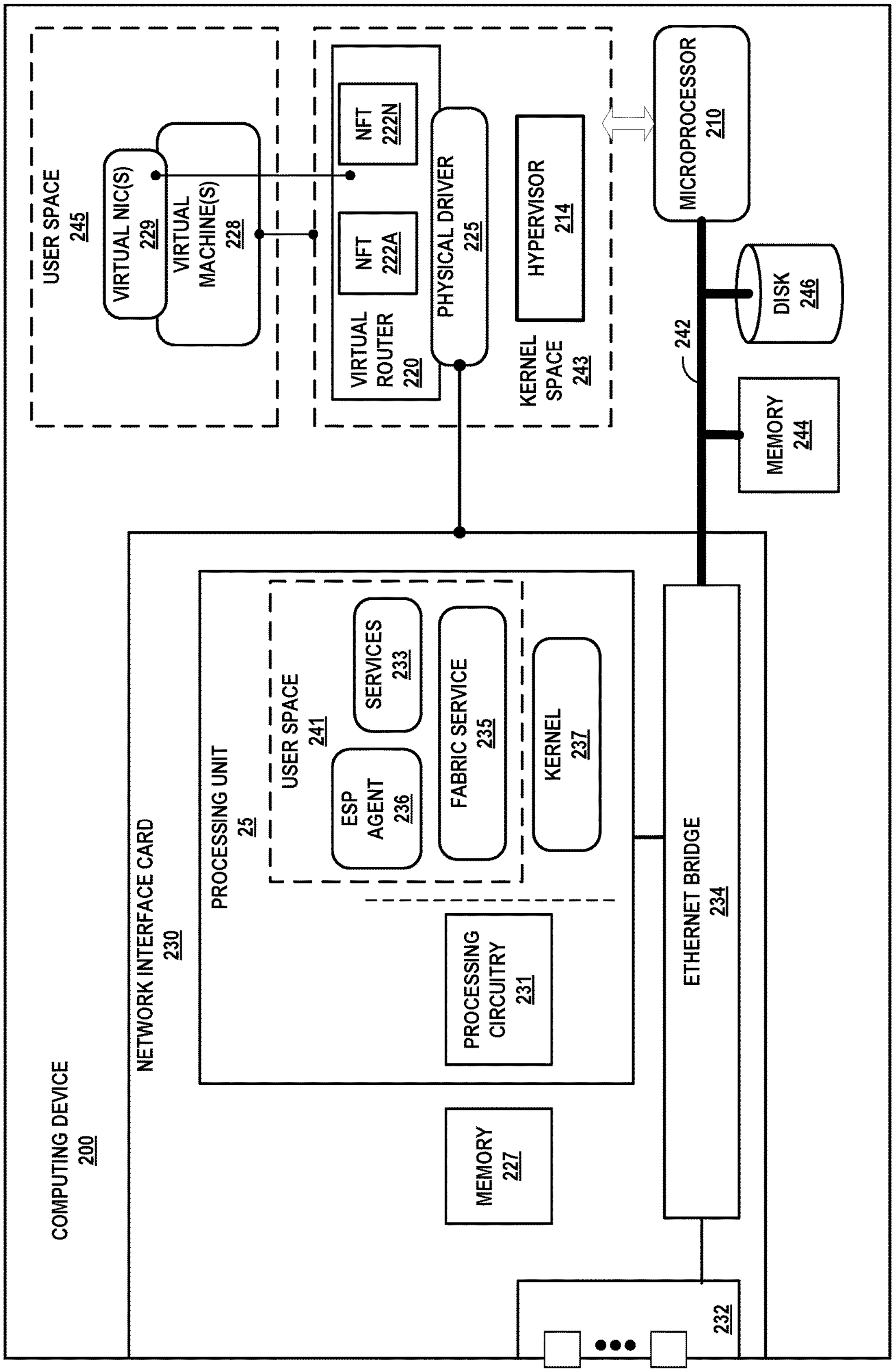
COMPUTING DEVICE 200
USER SPACE 245
VIRTUAL NIC(S) 229
VIRTUAL MACHINE(S) 228
VIRTUAL ROUTER 220
NFT 222A
NFT 222N
PHYSICAL DRIVER 225
HYPERVISOR 214
KERNEL SPACE 243
MICROPROCESSOR 210
DISK 246
242
MEMORY 244
NETWORK INTERFACE CARD 230
PROCESSING UNIT 25
USER SPACE 241
ESP AGENT 236
SERVICES 233
FABRIC SERVICE 235
KERNEL 237
PROCESSING CIRCUITRY 231
MEMORY 227
ETHERNET BRIDGE 234
232

FIG. 2

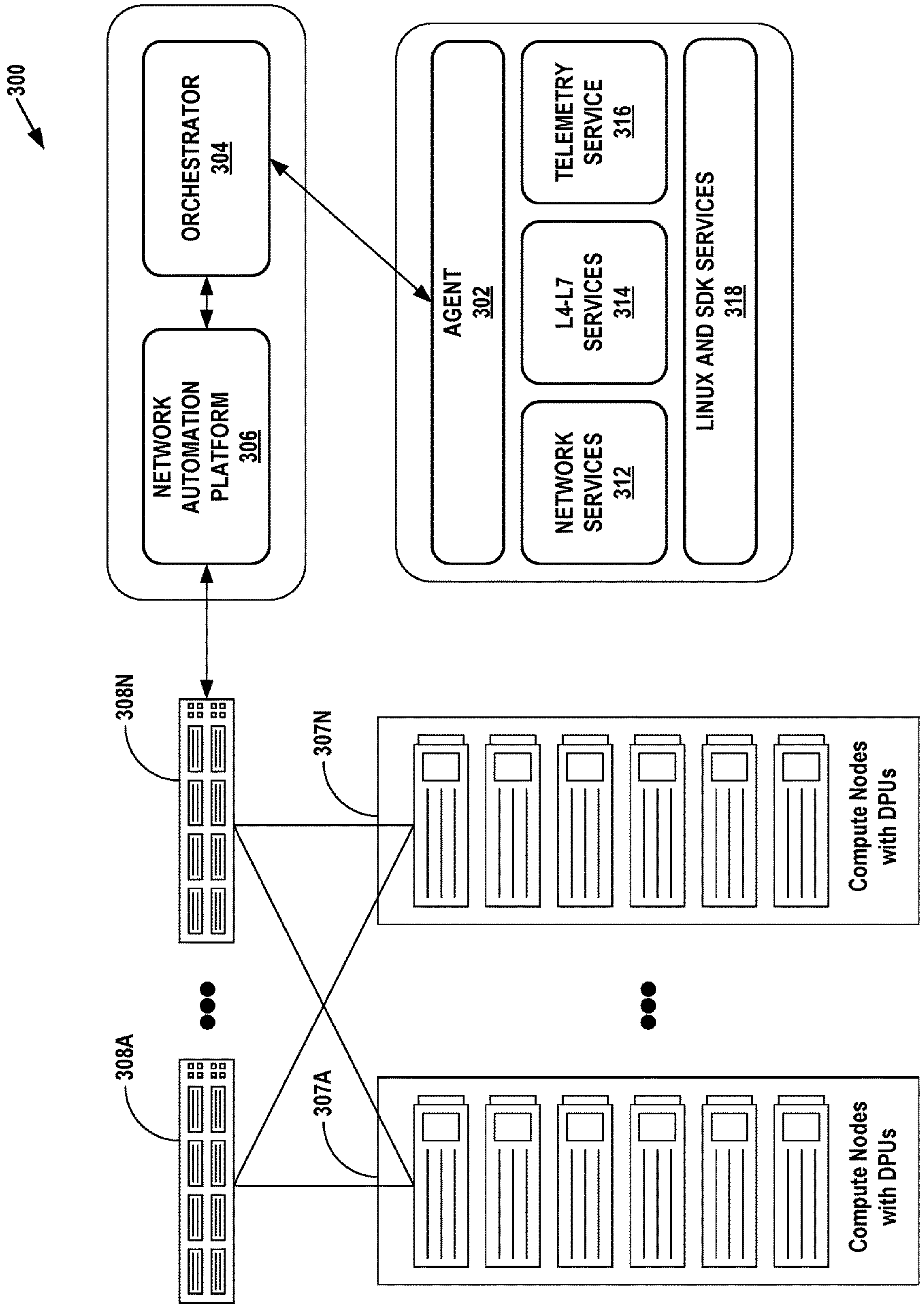
300
ORCHESTRATOR 304
NETWORK AUTOMATION PLATFORM 306
AGENT 302
TELEMETRY SERVICE 316
L4-L7 SERVICES 314
NETWORK SERVICES 312
LINUX AND SDK SERVICES 318
308N
308A
307N
307A
Compute Nodes with DPUs
Compute Nodes with DPUs

FIG. 3

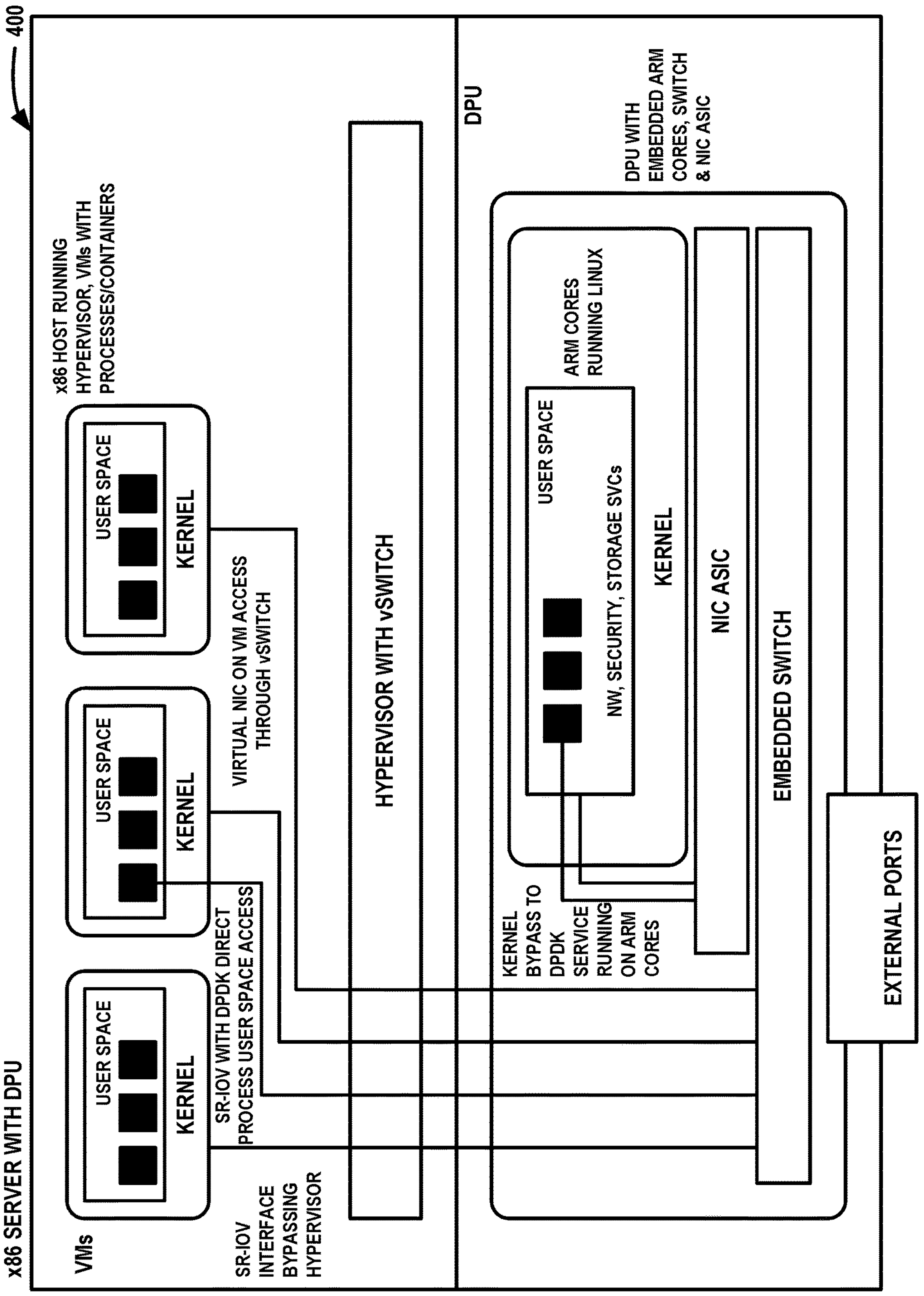
400
x86 SERVER WITH DPU
VMs
SR-IOV INTERFACE BYPASSING HYPERVISOR
USER SPACE
KERNEL
USER SPACE
KERNEL
USER SPACE
KERNEL
x86 HOST RUNNING HYPERVISOR, VMs WITH PROCESSES/CONTAINERS
SR-IOV WITH DPDK DIRECT PROCESS USER SPACE ACCESS
VIRTUAL NIC ON VM ACCESS THROUGH vSWITCH
HYPERVISOR WITH vSWITCH
DPU
KERNEL BYPASS TO DPDK SERVICE RUNNING ON ARM CORES
USER SPACE
NW, SECURITY, STORAGE SVCs
ARM CORES RUNNING LINUX
KERNEL
NIC ASIC
EMBEDDED SWITCH
DPU WITH EMBEDDED ARM CORES, SWITCH & NIC ASIC
EXTERNAL PORTS

FIG. 4

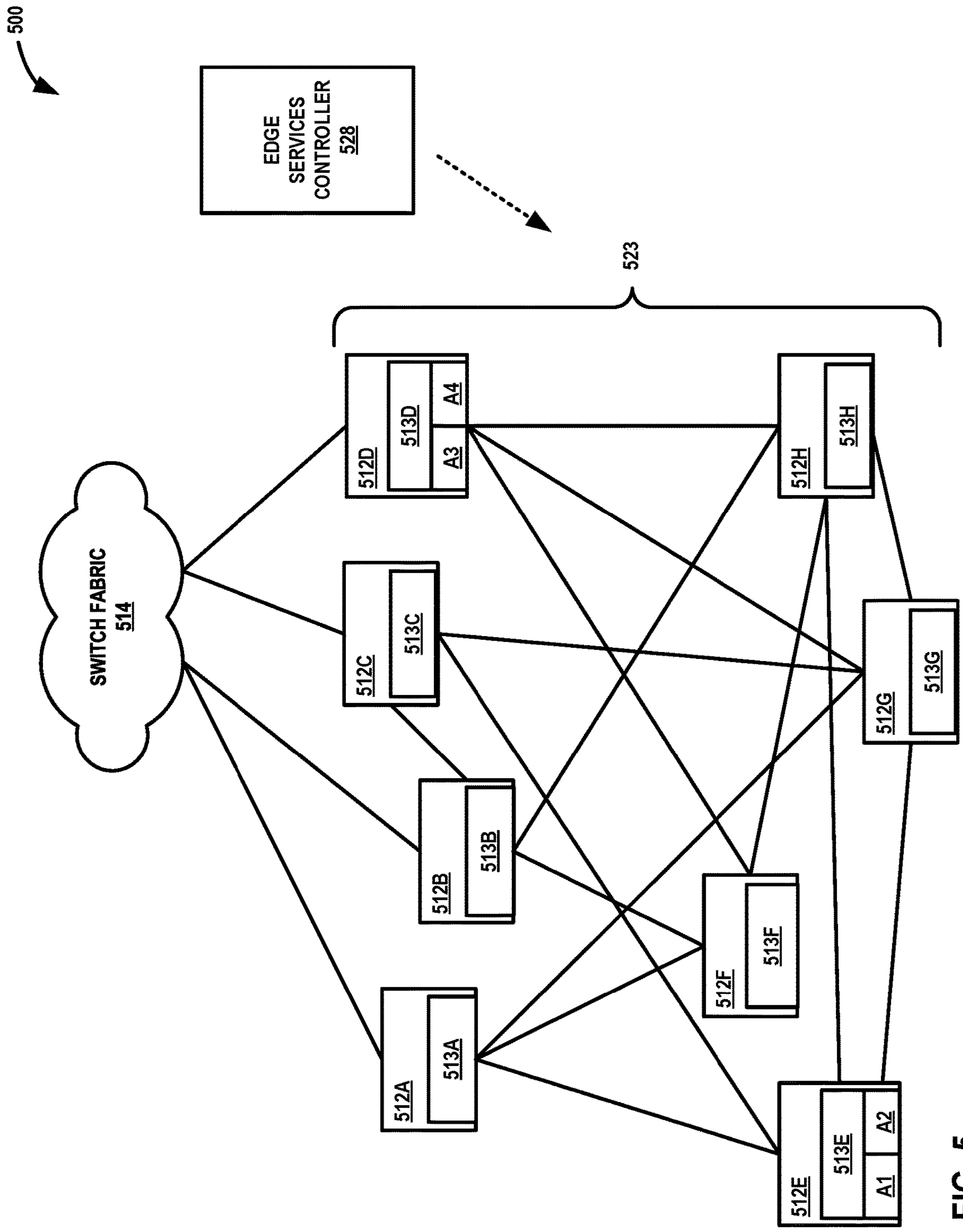
500
EDGE SERVICES CONTROLLER 528
523
SWITCH FABRIC 514
512D
513D
A3
A4
512H
513H
512C
513C
512G
513G
512B
513B
512F
513F
512A
513A
512E
513E
A1
A2

FIG. 5

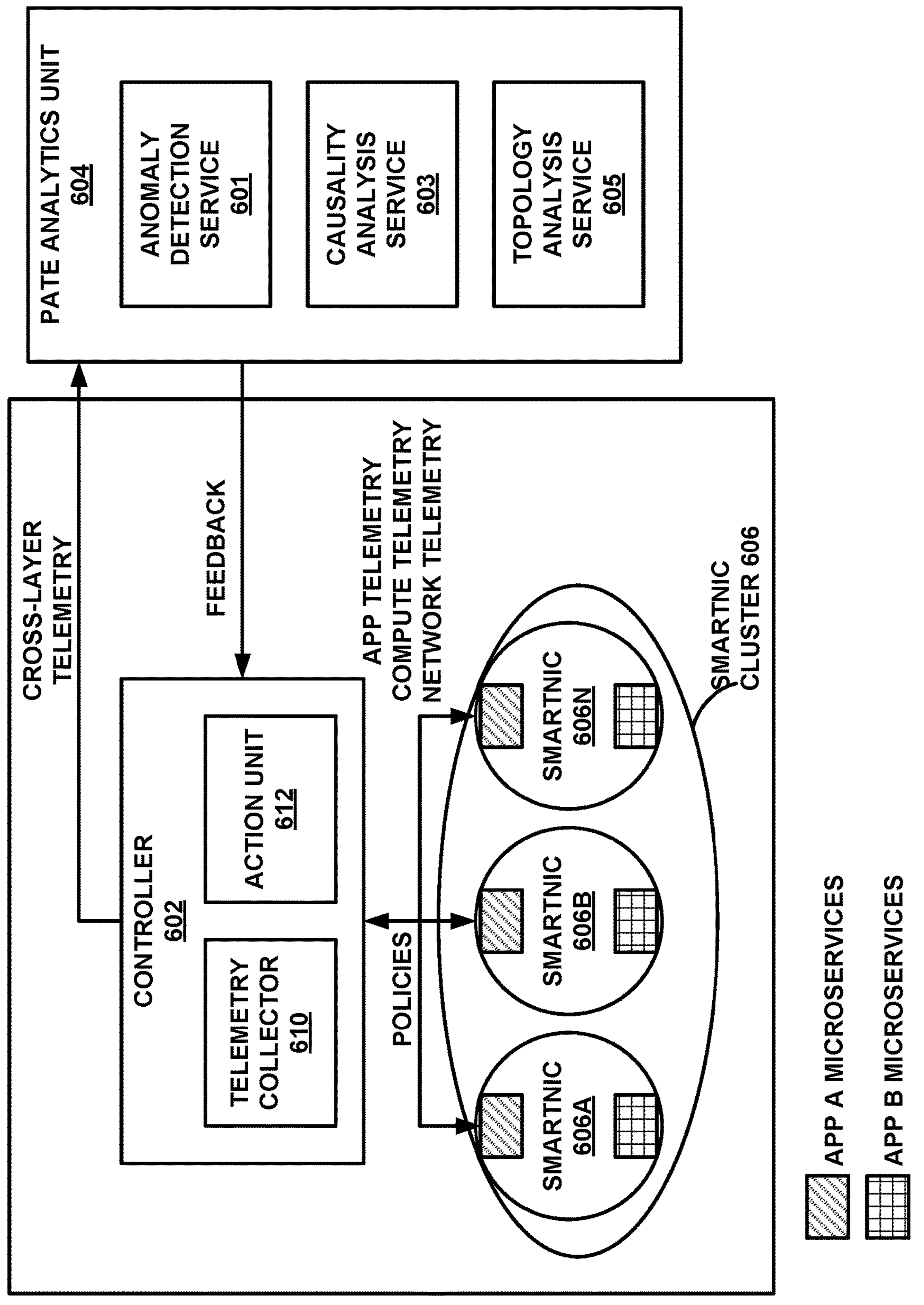
PATE ANALYTICS UNIT 604
ANOMALY DETECTION SERVICE 601
CAUSALITY ANALYSIS SERVICE 603
TOPOLOGY ANALYSIS SERVICE 605
CROSS-LAYER TELEMETRY
FEEDBACK
APP TELEMETRY
COMPUTE TELEMETRY
NETWORK TELEMETRY
CONTROLLER 602
TELEMETRY COLLECTOR 610
ACTION UNIT 612
POLICIES
SMARTNIC 606A
SMARTNIC 606B
SMARTNIC 606N
SMARTNIC CLUSTER 606
APP A MICROSERVICES
APP B MICROSERVICES

FIG. 6

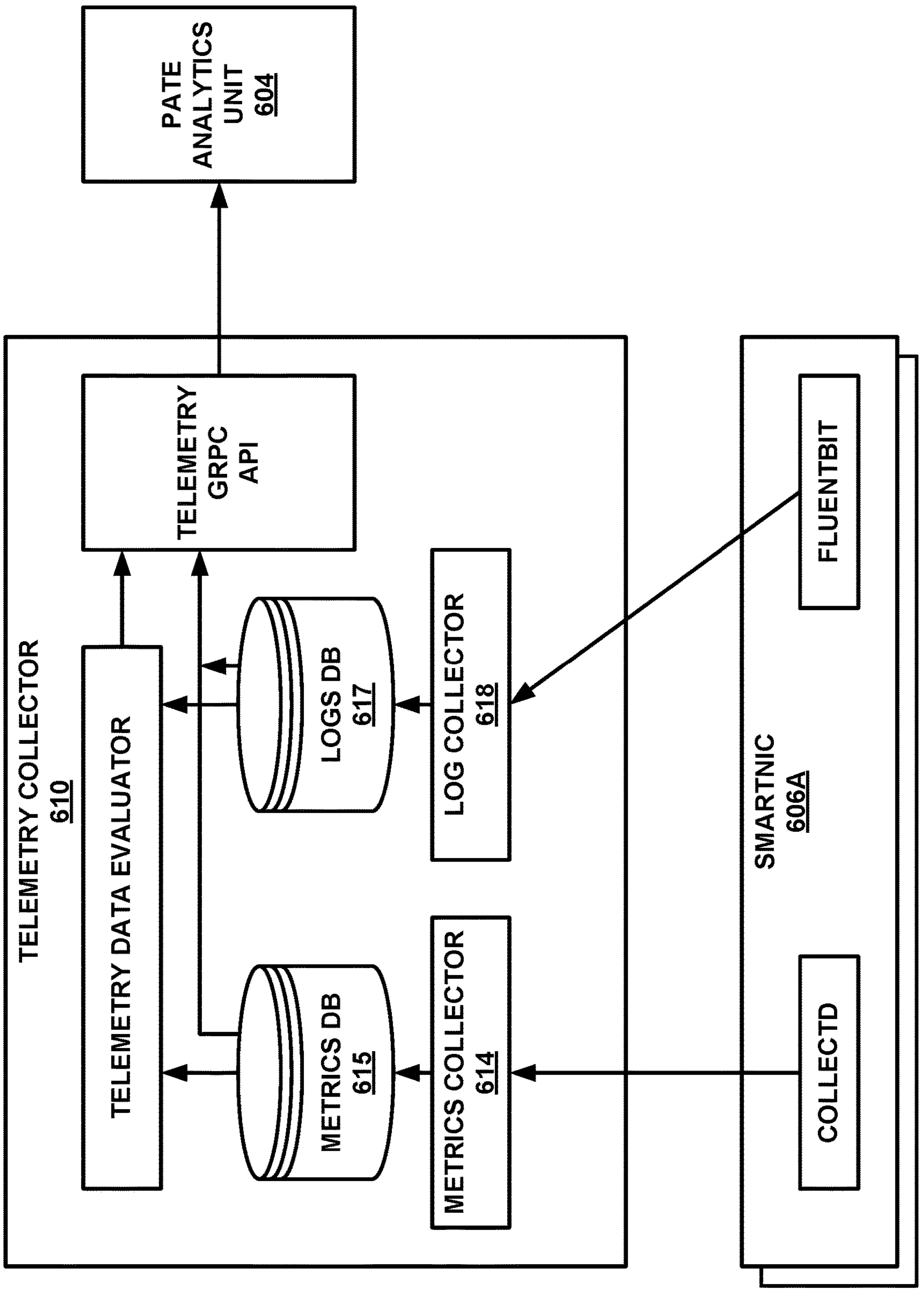
PATE ANALYTICS UNIT 604
TELEMETRY COLLECTOR 610
TELEMETRY GRPC API
TELEMETRY DATA EVALUATOR
LOGS DB 617
LOG COLLECTOR 618
METRICS DB 615
METRICS COLLECTOR 614
SMARTNIC 606A
FLUENTBIT
COLLECTD

FIG. 7

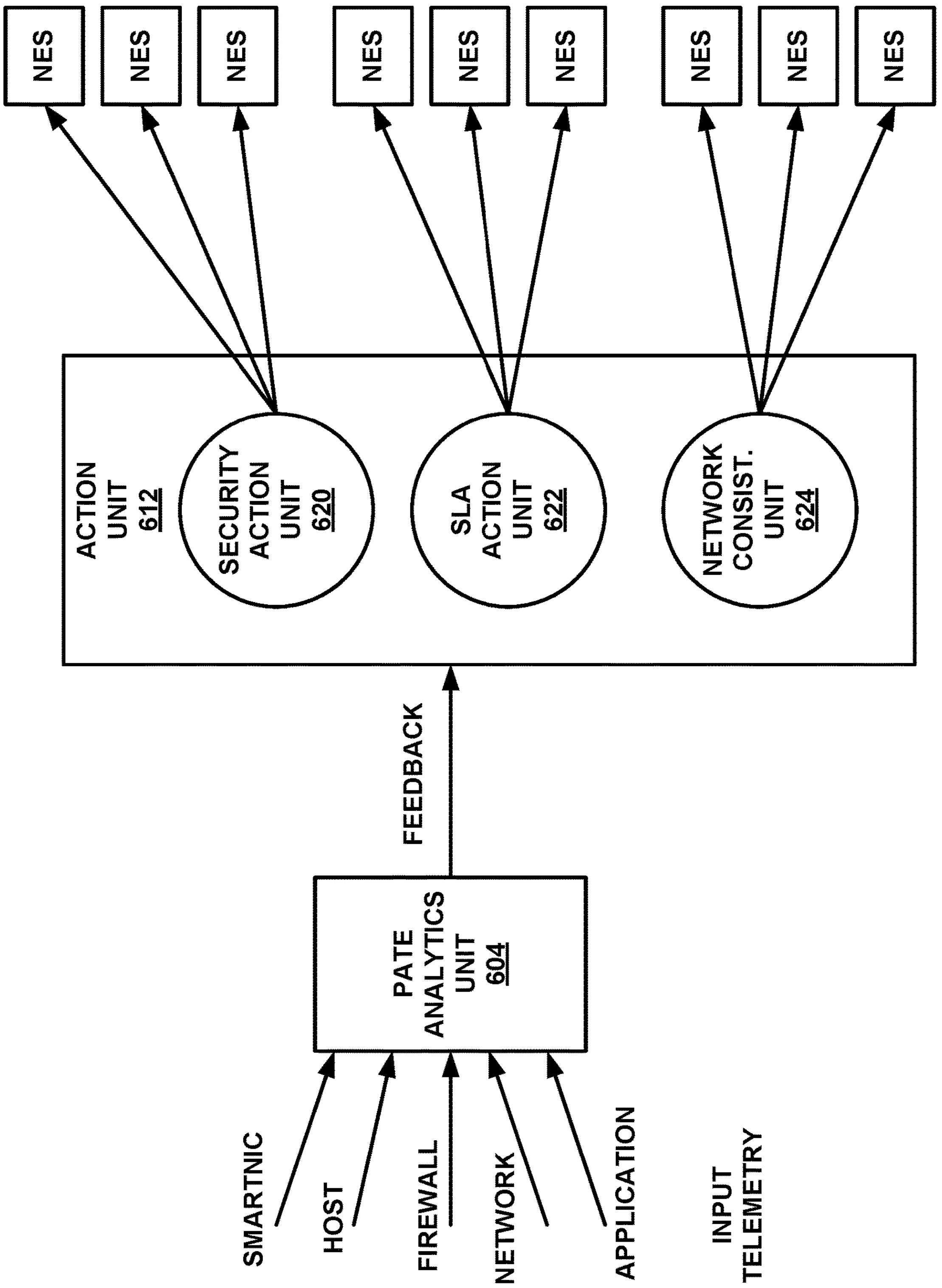
INPUT TELEMETRY
SMARTNIC
HOST
FIREWALL
NETWORK
APPLICATION
PATE ANALYTICS UNIT 604
FEEDBACK
ACTION UNIT 612
SECURITY ACTION UNIT 620
SLA ACTION UNIT 622
NETWORK CONSIST. UNIT 624
NES
NES
NES
NES
NES
NES
NES
NES
NES

FIG. 8

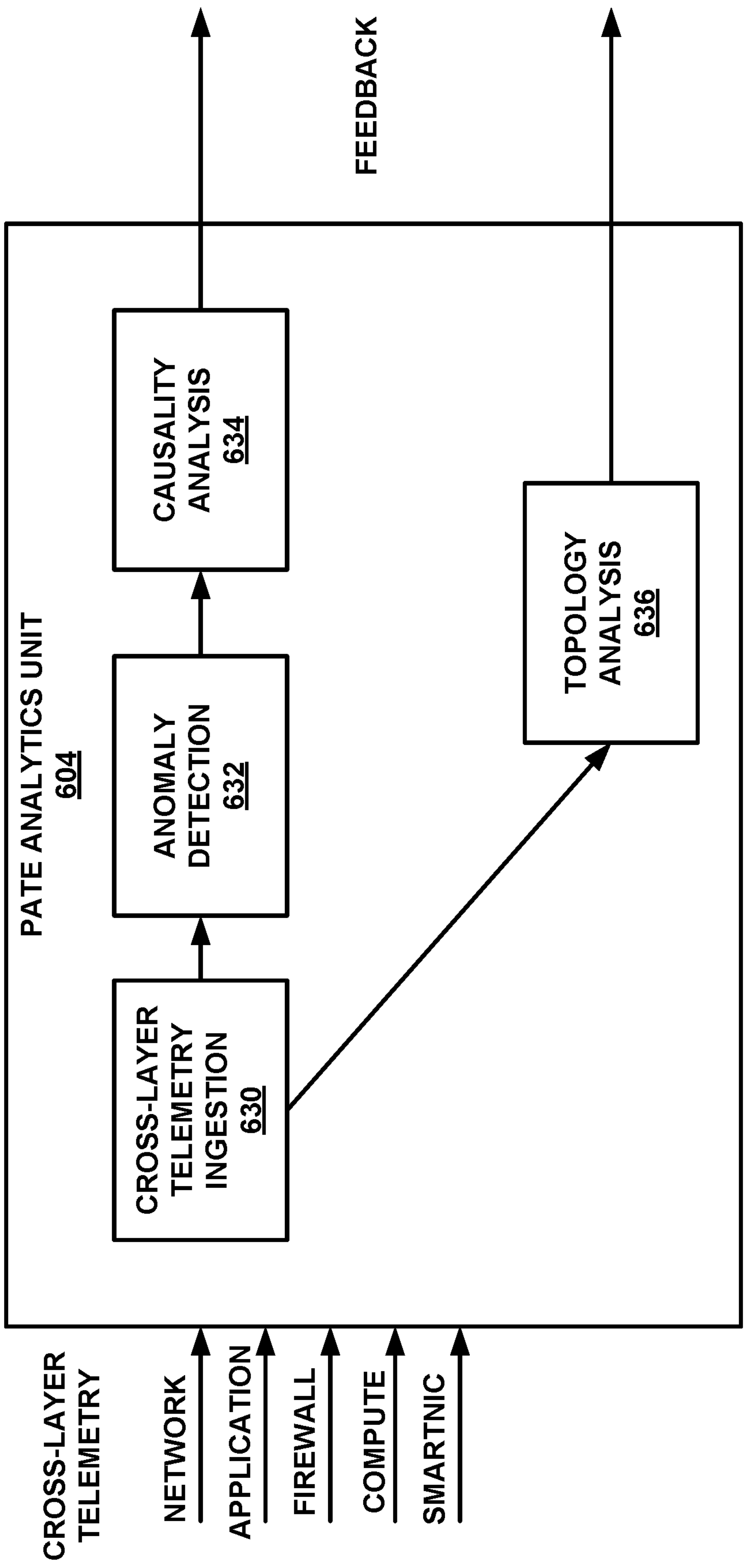
CROSS-LAYER TELEMETRY
NETWORK
APPLICATION
FIREWALL
COMPUTE
SMARTNIC
PATE ANALYTICS UNIT 604
CROSS-LAYER TELEMETRY INGESTION 630
ANOMALY DETECTION 632
CAUSALITY ANALYSIS 634
TOPOLOGY ANALYSIS 636
FEEDBACK

FIG. 9

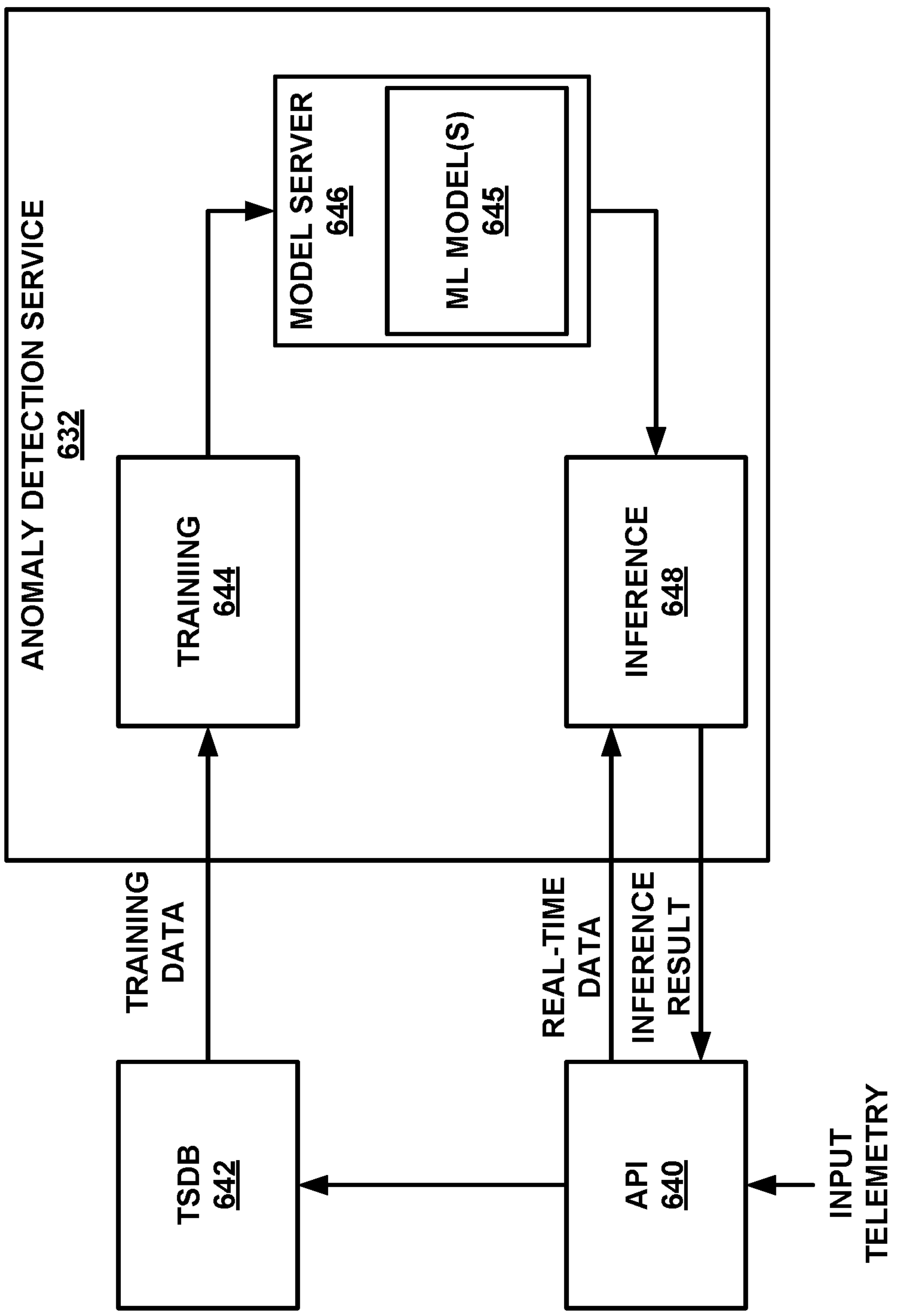
ANOMALY DETECTION SERVICE 632
TRAINIING 644
MODEL SERVER 646
ML MODEL(S) 645
INFERENCE 648
TRAINING DATA
REAL-TIME DATA
INFERENCE RESULT
TSDB 642
API 640
INPUT TELEMETRY

FIG. 10

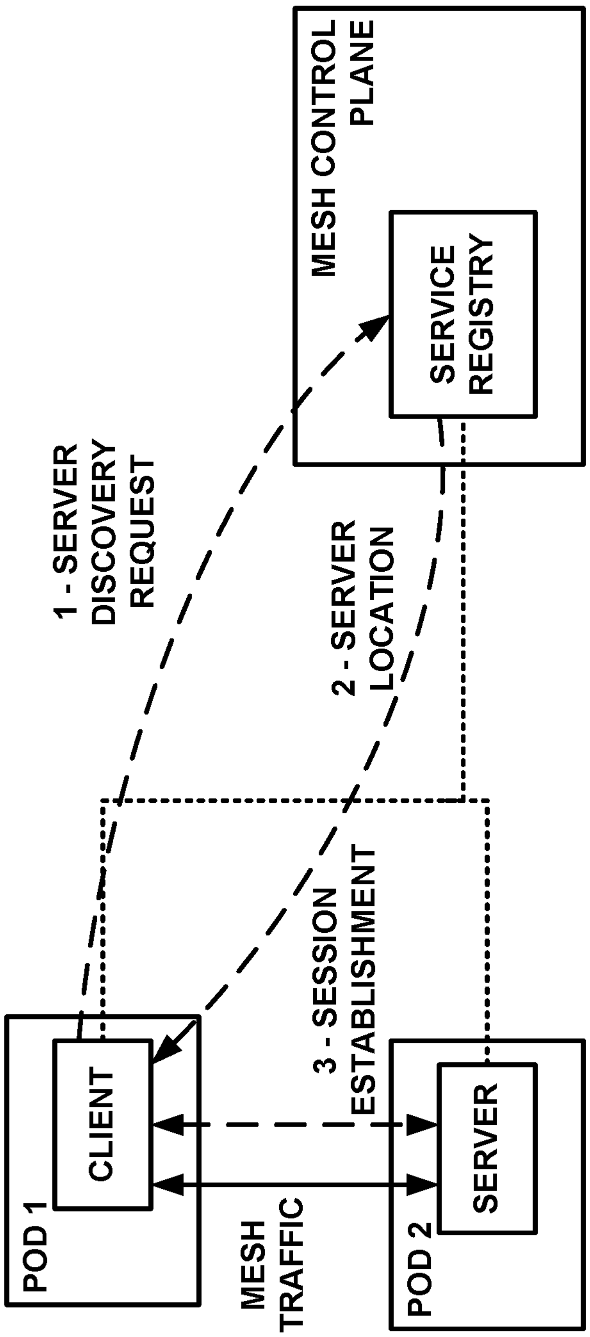
MESH CONTROL PLANE
SERVICE REGISTRY
1 - SERVER DISCOVERY REQUEST
2 - SERVER LOCATION
3 - SESSION ESTABLISHMENT
POD 1
CLIENT
MESH TRAFFIC
POD 2
SERVER

FIG. 11A

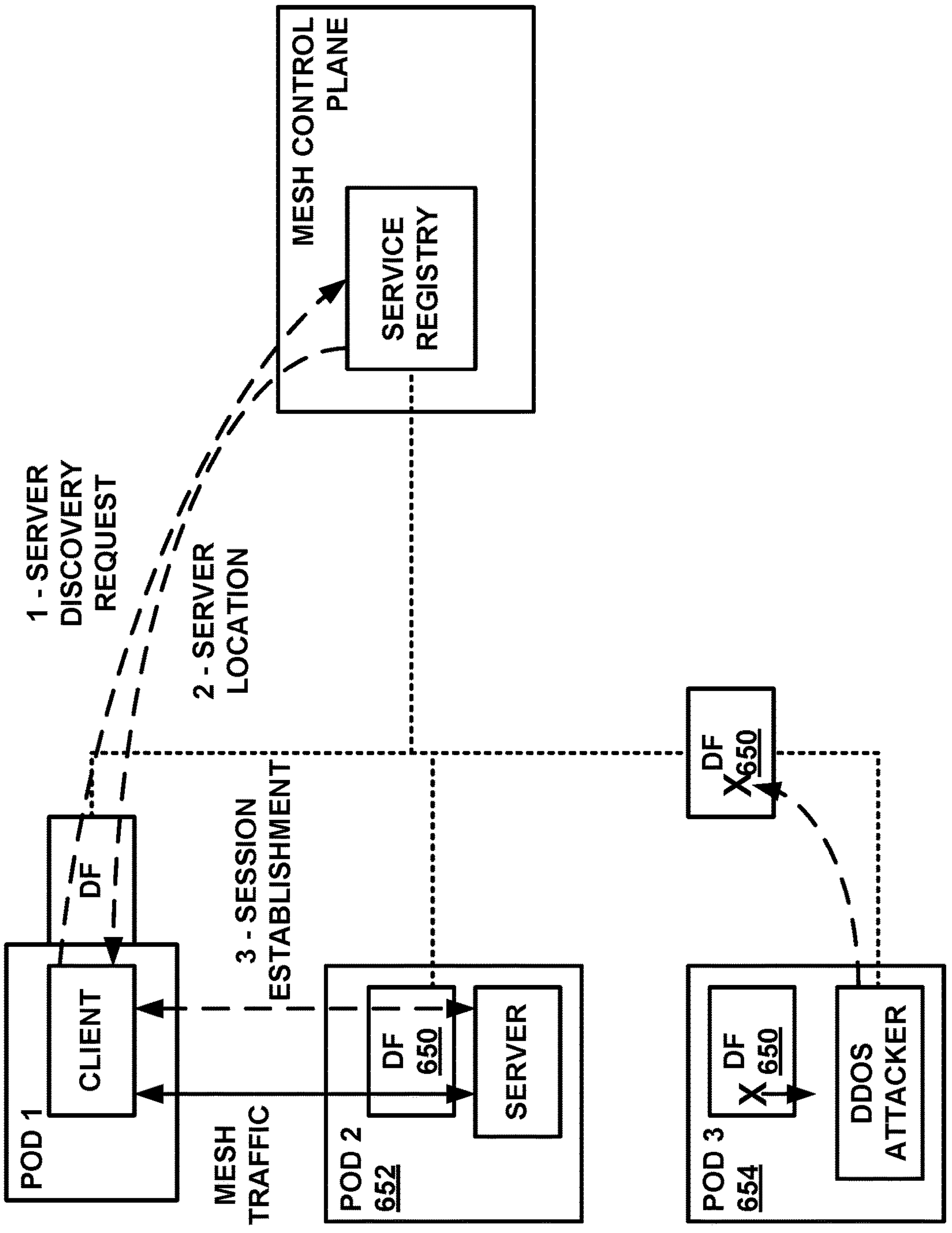
MESH CONTROL PLANE
SERVICE REGISTRY
1 - SERVER DISCOVERY REQUEST
2 - SERVER LOCATION
3 - SESSION ESTABLISHMENT
MESH TRAFFIC
DF
CLIENT
POD 1
POD 2 652
DF 650
SERVER
POD 3 654
DF 650
X
DDOS ATTACKER
DF
X 650

FIG. 11B

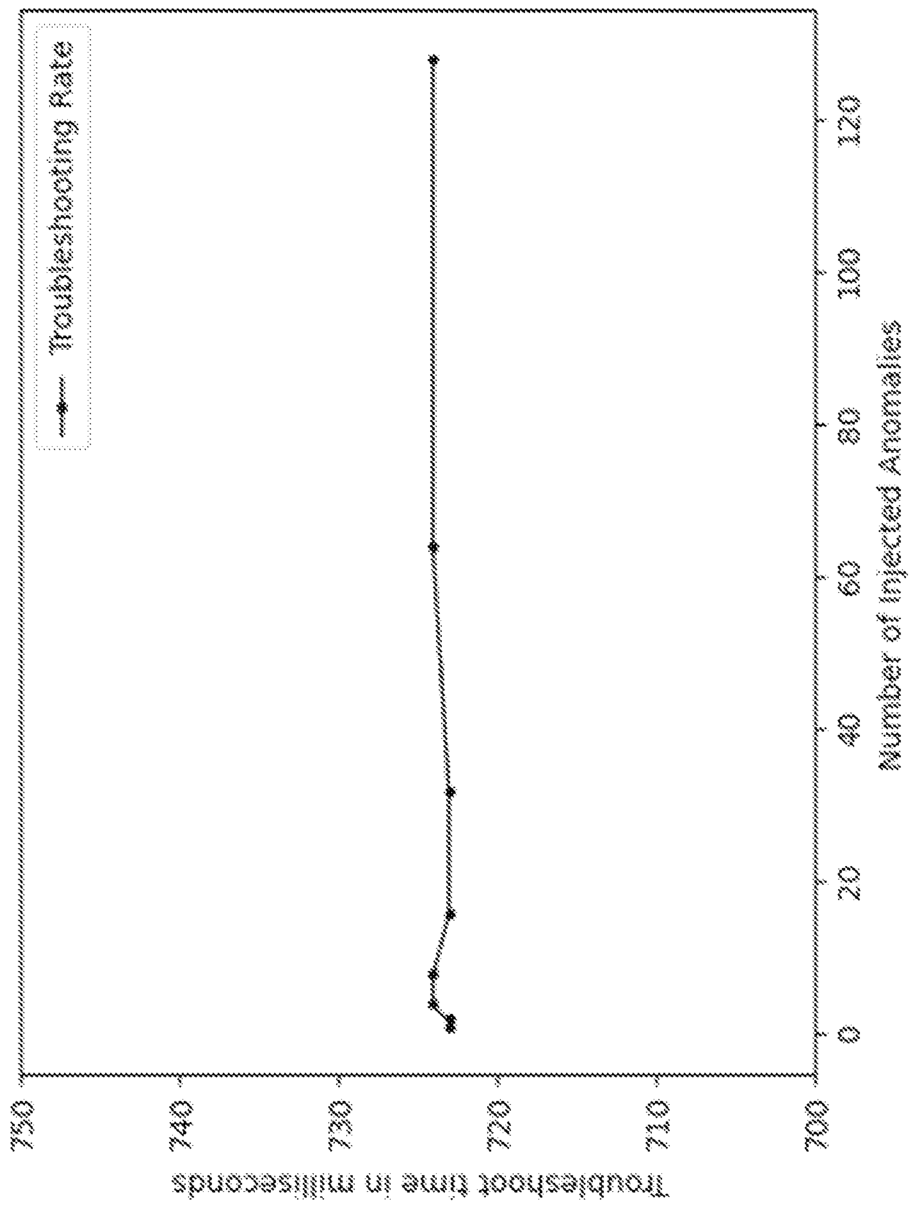
Troubleshooting Rate
Troubleshoot time in milliseconds
750
740
730
720
710
700
0
20
40
60
80
100
120
Number of Injected Anomalies

FIG. 12

	Precision	Recall	F1-score	Support
0	1.00	1.00	1.00	6276
1	0.94	1.00	0.97	232
Accuracy			1.00	6508
Macro avg	0.97	1.00	0.98	6508
Weighted avg	1.00	1.00	1.00	6508

FIG. 13

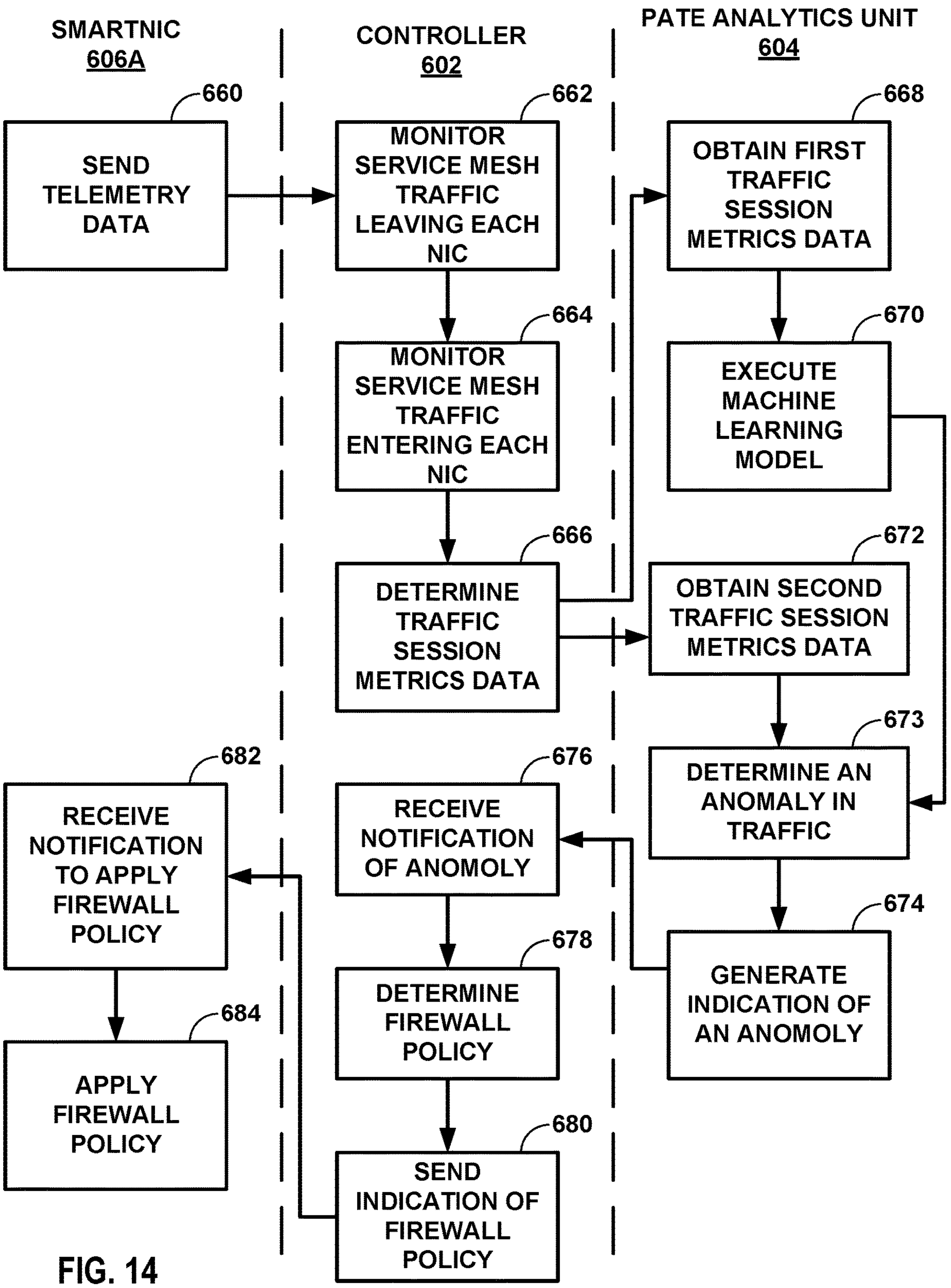
SMARTNIC
606A
CONTROLLER
602
PATE ANALYTICS UNIT
604
660
SEND TELEMETRY DATA
662
MONITOR SERVICE MESH TRAFFIC LEAVING EACH NIC
664
MONITOR SERVICE MESH TRAFFIC ENTERING EACH NIC
666
DETERMINE TRAFFIC SESSION METRICS DATA
668
OBTAIN FIRST TRAFFIC SESSION METRICS DATA
670
EXECUTE MACHINE LEARNING MODEL
672
OBTAIN SECOND TRAFFIC SESSION METRICS DATA
673
DETERMINE AN ANOMALY IN TRAFFIC
674
GENERATE INDICATION OF AN ANOMOLY
676
RECEIVE NOTIFICATION OF ANOMOLY
678
DETERMINE FIREWALL POLICY
680
SEND INDICATION OF FIREWALL POLICY
682
RECEIVE NOTIFICATION TO APPLY FIREWALL POLICY
684
APPLY FIREWALL POLICY

FIG. 14

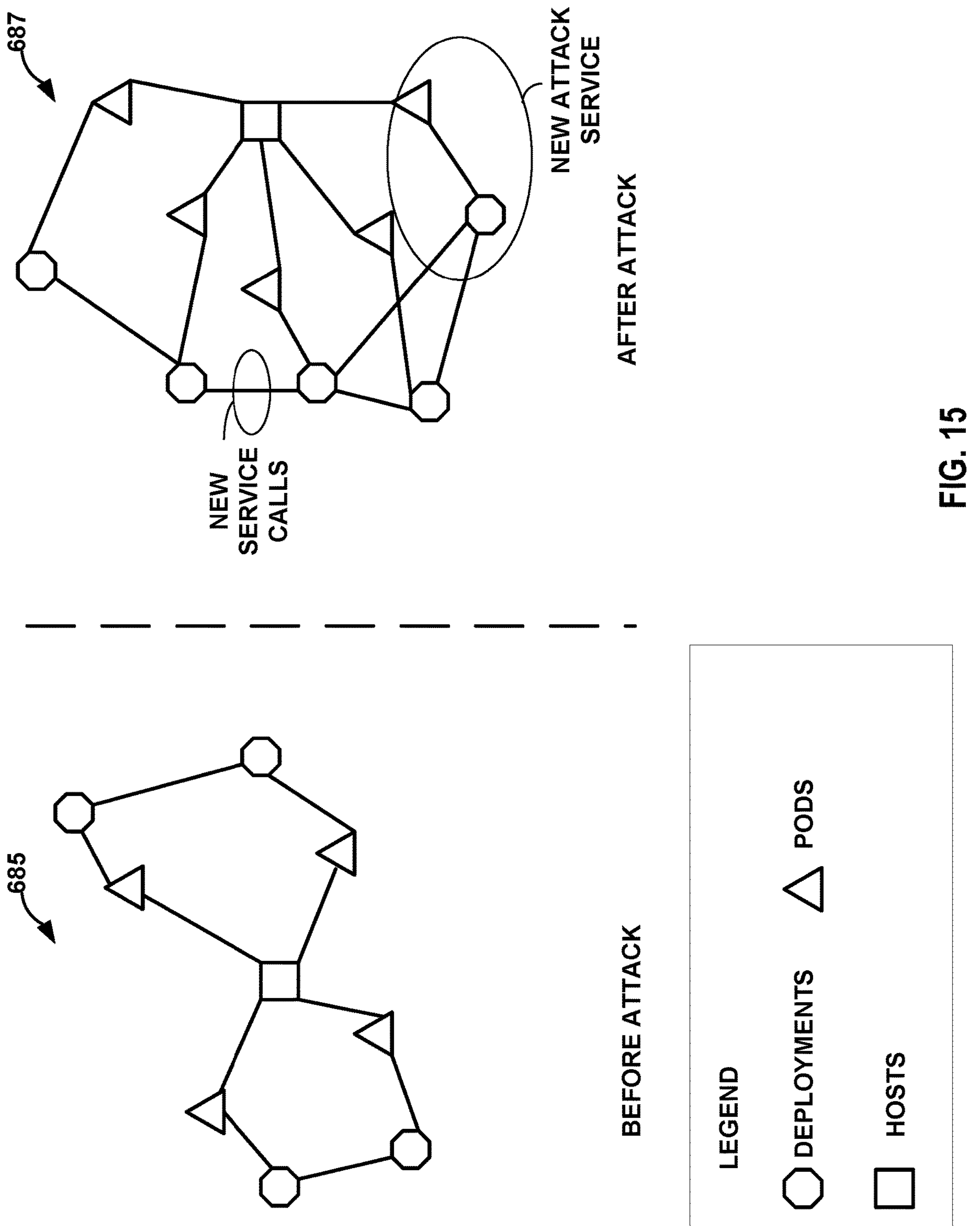
685
BEFORE ATTACK
687
NEW SERVICE CALLS
NEW ATTACK SERVICE
AFTER ATTACK
LEGEND
DEPLOYMENTS
PODS
HOSTS

FIG. 15

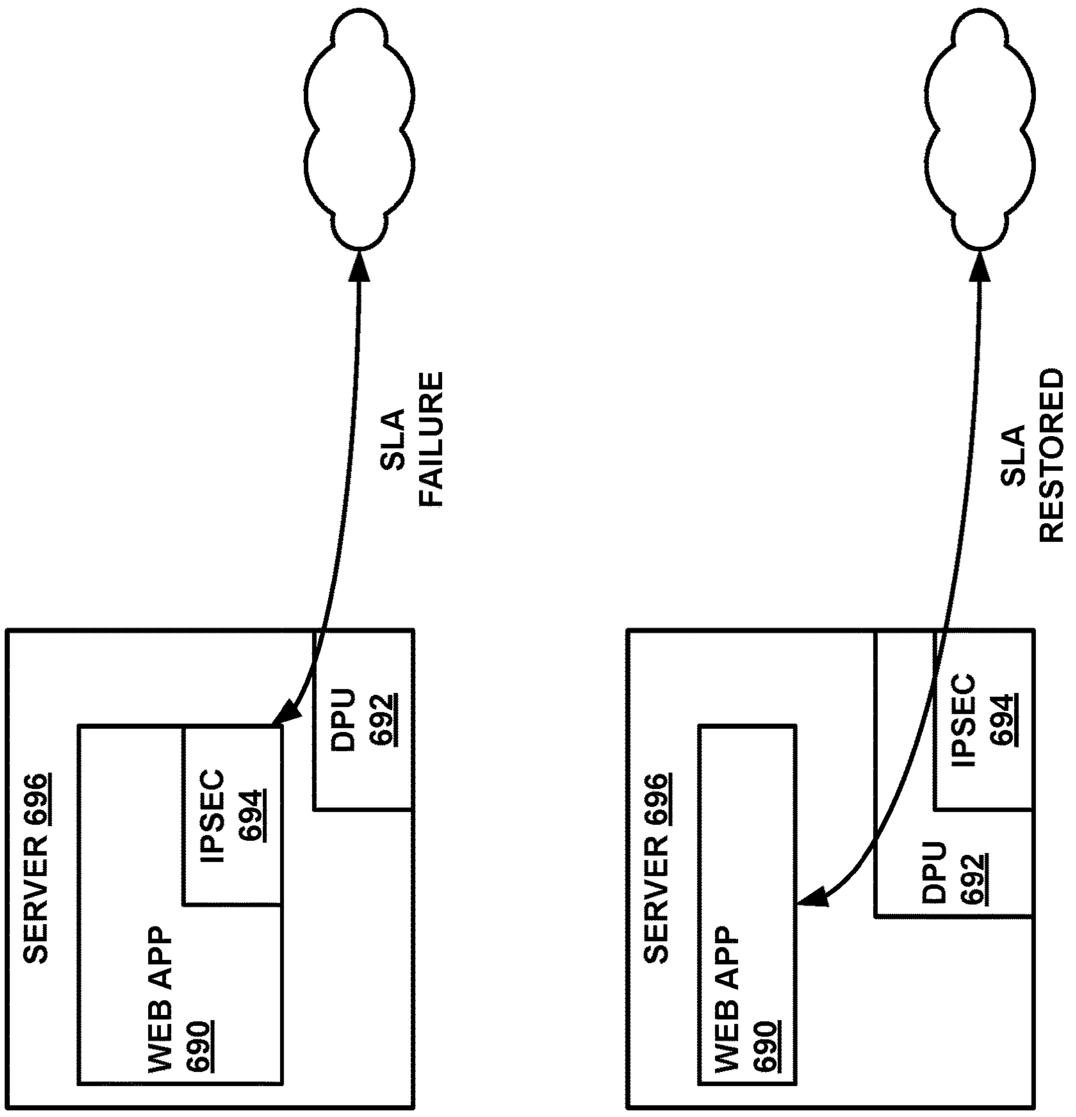
SERVER 696
WEB APP 690
IPSEC 694
DPU 692
SLA FAILURE
SERVER 696
WEB APP 690
DPU 692
IPSEC 694
SLA RESTORED

FIG. 16

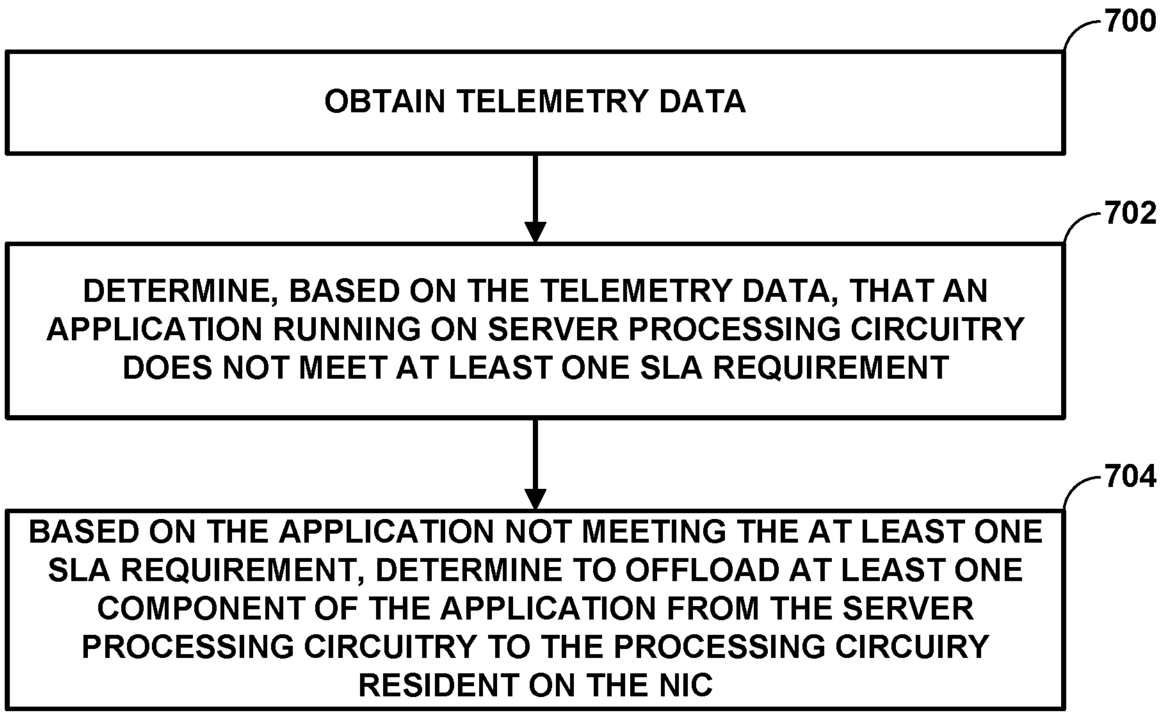
700
OBTAIN TELEMETRY DATA
702
DETERMINE, BASED ON THE TELEMETRY DATA, THAT AN APPLICATION RUNNING ON SERVER PROCESSING CIRCUITRY DOES NOT MEET AT LEAST ONE SLA REQUIREMENT
704
BASED ON THE APPLICATION NOT MEETING THE AT LEAST ONE SLA REQUIREMENT, DETERMINE TO OFFLOAD AT LEAST ONE COMPONENT OF THE APPLICATION FROM THE SERVER PROCESSING CIRCUITRY TO THE PROCESSING CIRCUIRY RESIDENT ON THE NIC

FIG. 17

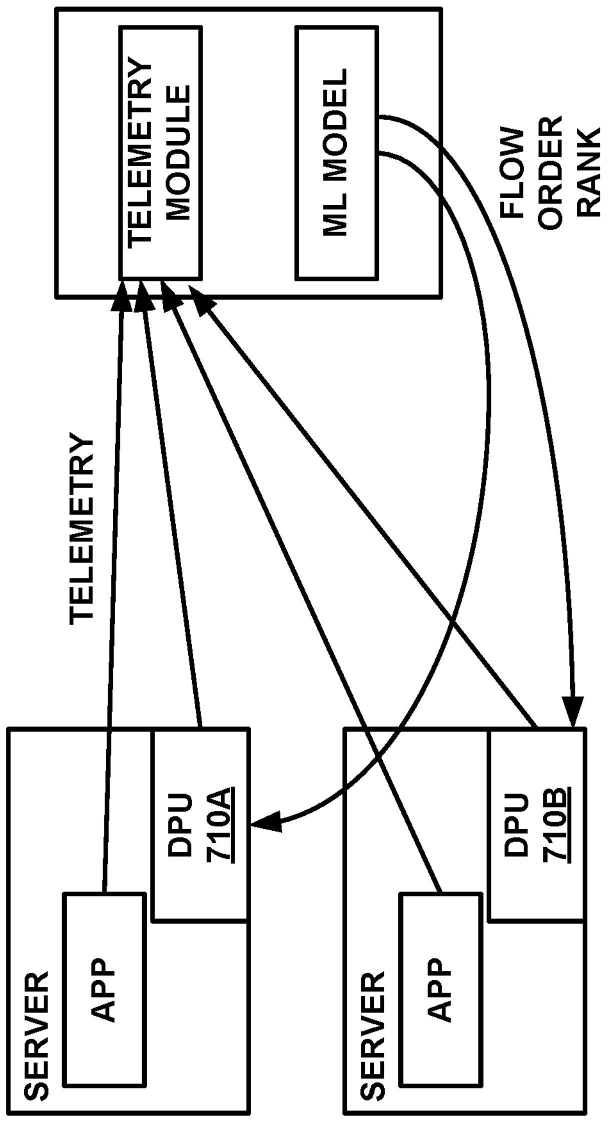
TELEMETRY MODULE
ML MODEL
FLOW ORDER RANK
TELEMETRY
SERVER
APP
DPU 710A
SERVER
APP
DPU 710B

FIG. 18

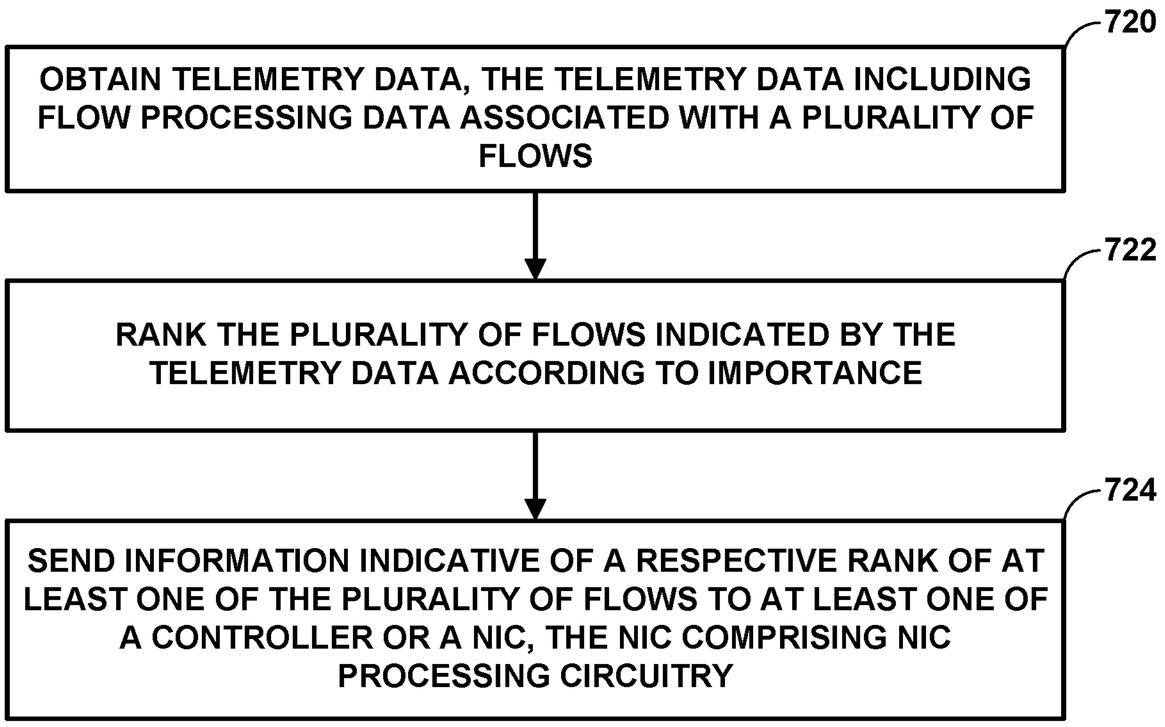
720
OBTAIN TELEMETRY DATA, THE TELEMETRY DATA INCLUDING FLOW PROCESSING DATA ASSOCIATED WITH A PLURALITY OF FLOWS
722
RANK THE PLURALITY OF FLOWS INDICATED BY THE TELEMETRY DATA ACCORDING TO IMPORTANCE
724
SEND INFORMATION INDICATIVE OF A RESPECTIVE RANK OF AT LEAST ONE OF THE PLURALITY OF FLOWS TO AT LEAST ONE OF A CONTROLLER OR A NIC, THE NIC COMPRISING NIC PROCESSING CIRCUITRY

FIG. 19

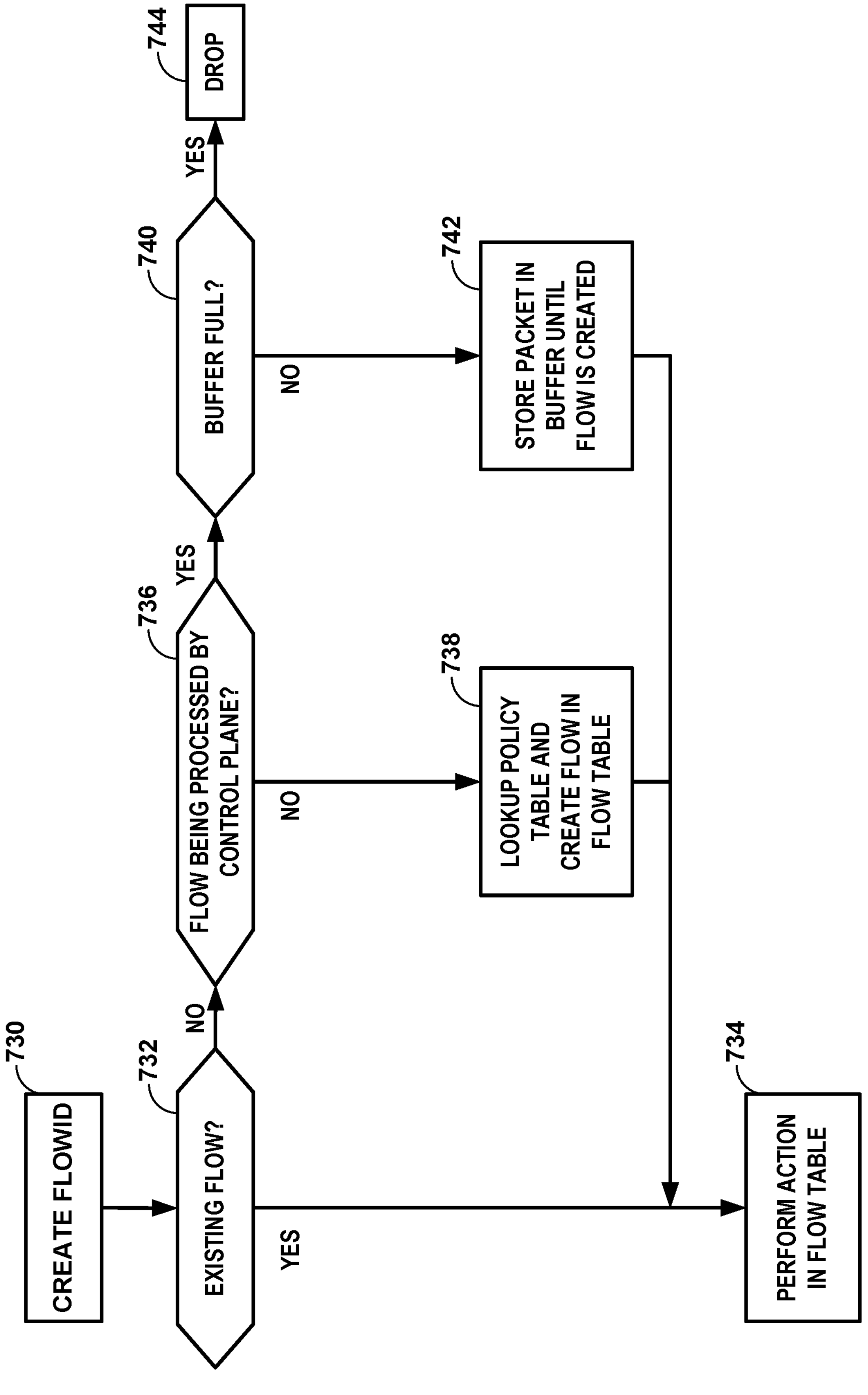
730
CREATE FLOWID
732
EXISTING FLOW?
YES
NO
734
PERFORM ACTION IN FLOW TABLE
736
FLOW BEING PROCESSED BY CONTROL PLANE?
NO
YES
738
LOOKUP POLICY TABLE AND CREATE FLOW IN FLOW TABLE
740
BUFFER FULL?
NO
YES
742
STORE PACKET IN BUFFER UNTIL FLOW IS CREATED
744
DROP

FIG. 20

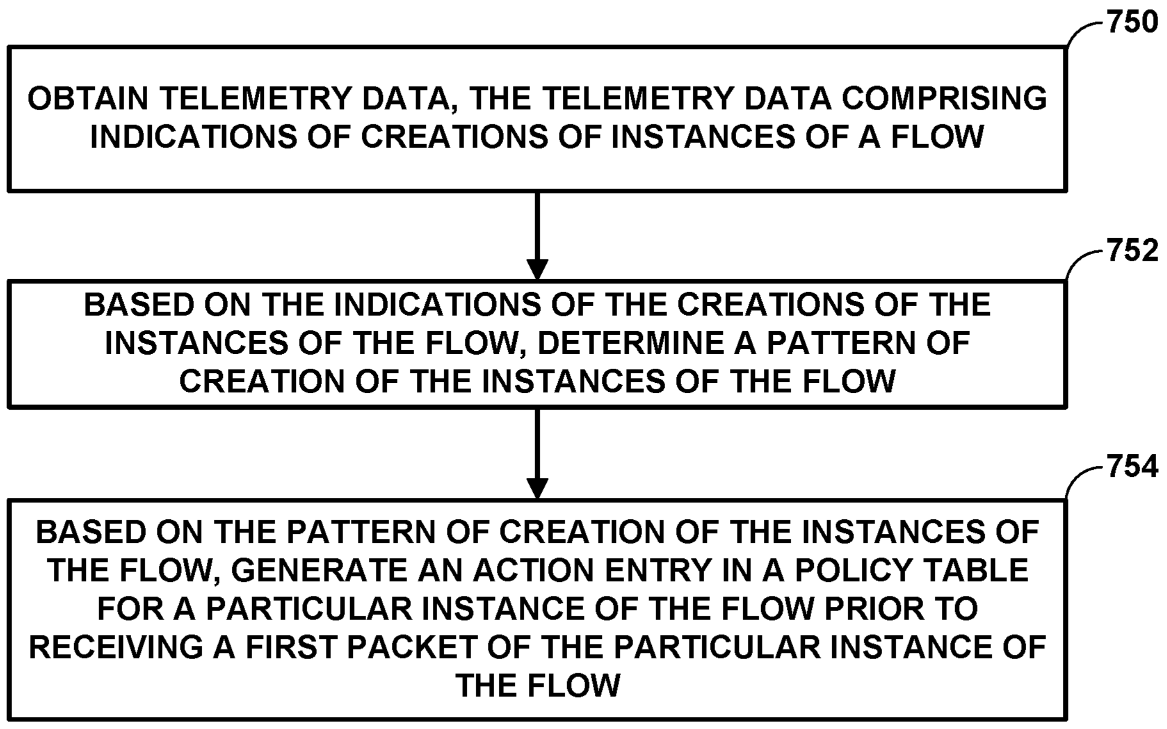
750
OBTAIN TELEMETRY DATA, THE TELEMETRY DATA COMPRISING INDICATIONS OF CREATIONS OF INSTANCES OF A FLOW
752
BASED ON THE INDICATIONS OF THE CREATIONS OF THE INSTANCES OF THE FLOW, DETERMINE A PATTERN OF CREATION OF THE INSTANCES OF THE FLOW
754
BASED ON THE PATTERN OF CREATION OF THE INSTANCES OF THE FLOW, GENERATE AN ACTION ENTRY IN A POLICY TABLE FOR A PARTICULAR INSTANCE OF THE FLOW PRIOR TO RECEIVING A FIRST PACKET OF THE PARTICULAR INSTANCE OF THE FLOW

FIG. 21

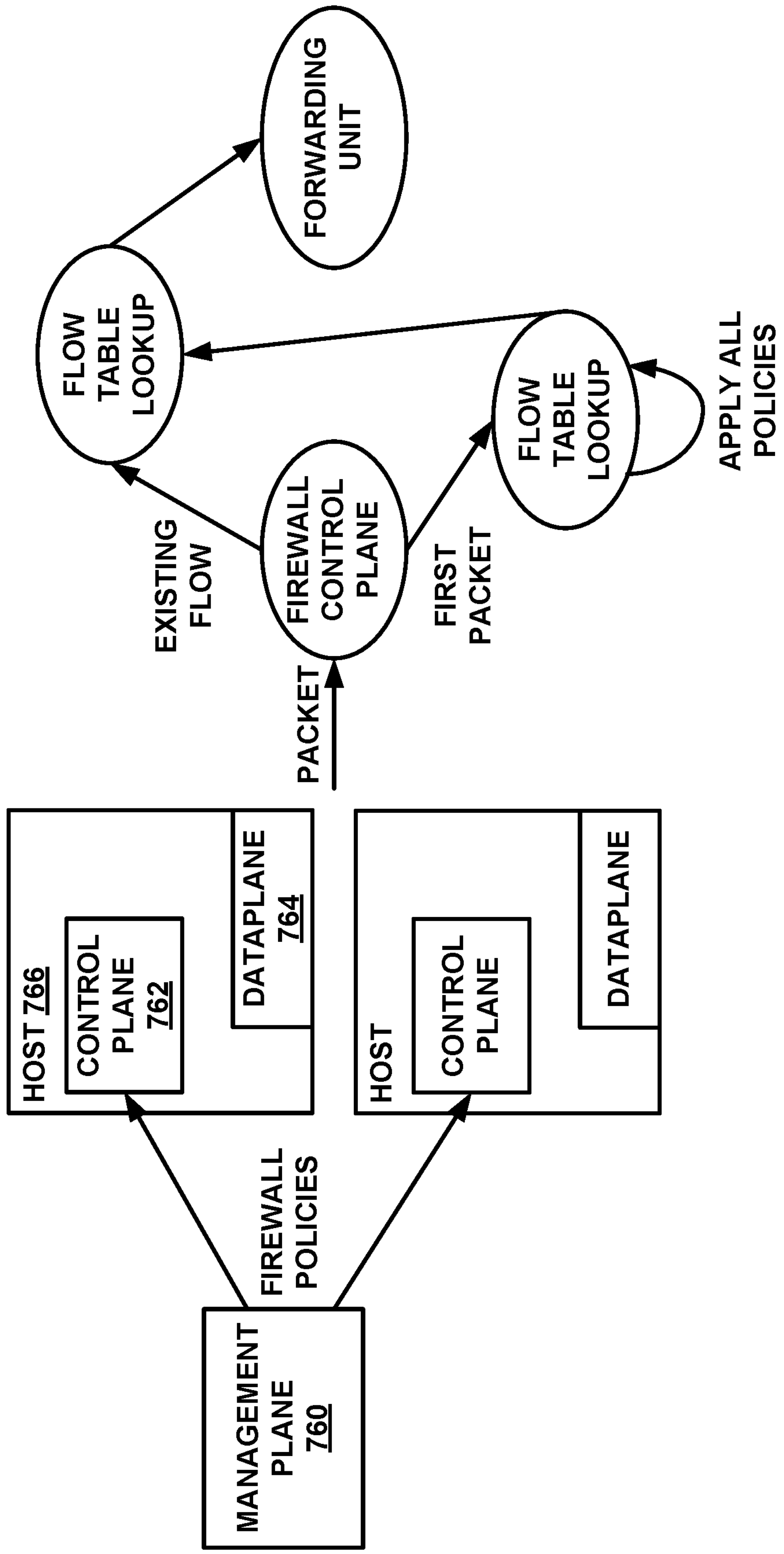
MANAGEMENT PLANE 760
FIREWALL POLICIES
HOST 766
CONTROL PLANE 762
DATAPLANE 764
HOST
CONTROL PLANE
DATAPLANE
PACKET
FIREWALL CONTROL PLANE
EXISTING FLOW
FIRST PACKET
FLOW TABLE LOOKUP
FLOW TABLE LOOKUP
APPLY ALL POLICIES
FORWARDING UNIT

FIG. 22

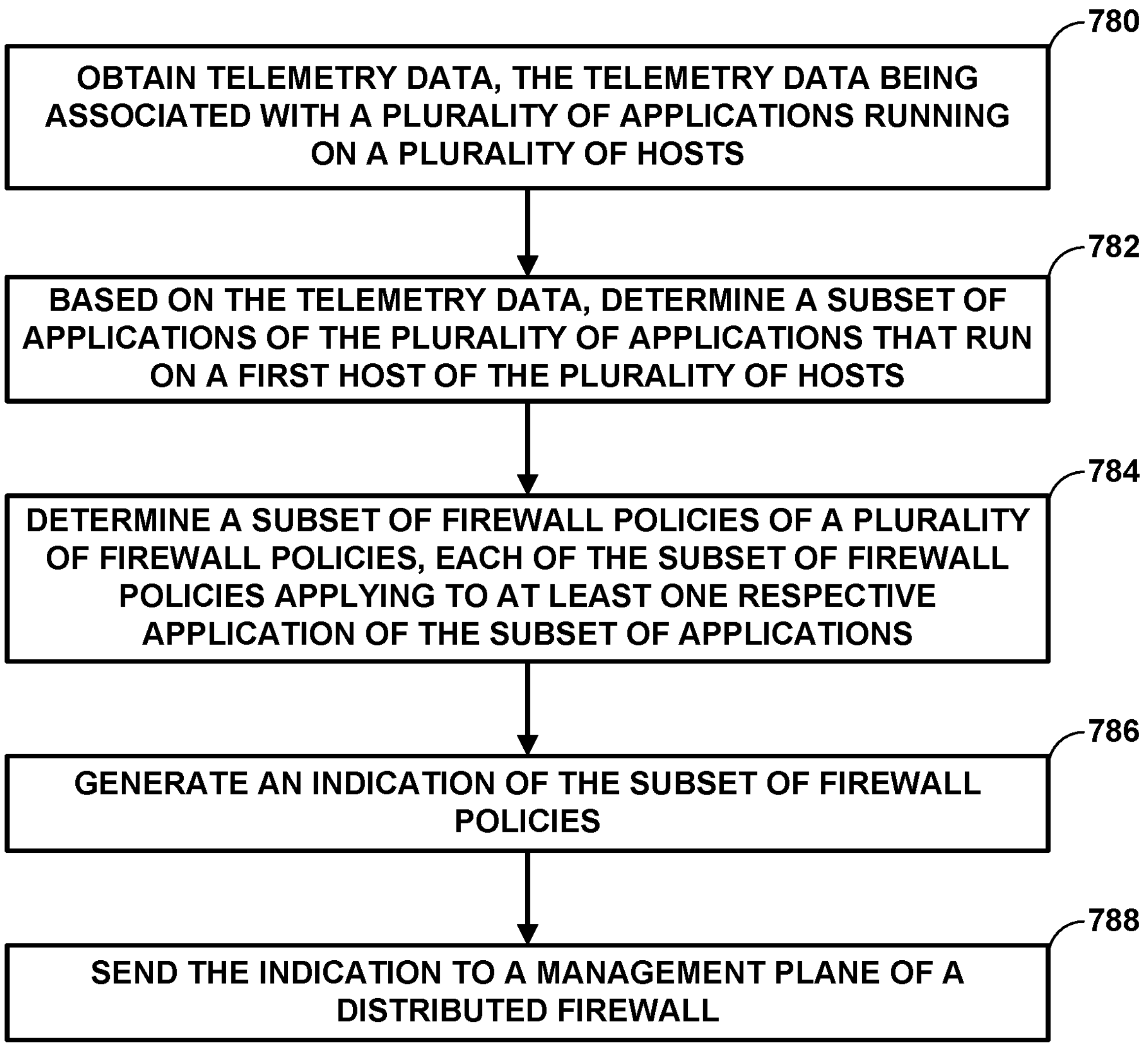
780
OBTAIN TELEMETRY DATA, THE TELEMETRY DATA BEING ASSOCIATED WITH A PLURALITY OF APPLICATIONS RUNNING ON A PLURALITY OF HOSTS
782
BASED ON THE TELEMETRY DATA, DETERMINE A SUBSET OF APPLICATIONS OF THE PLURALITY OF APPLICATIONS THAT RUN ON A FIRST HOST OF THE PLURALITY OF HOSTS
784
DETERMINE A SUBSET OF FIREWALL POLICIES OF A PLURALITY OF FIREWALL POLICIES, EACH OF THE SUBSET OF FIREWALL POLICIES APPLYING TO AT LEAST ONE RESPECTIVE APPLICATION OF THE SUBSET OF APPLICATIONS
786
GENERATE AN INDICATION OF THE SUBSET OF FIREWALL POLICIES
788
SEND THE INDICATION TO A MANAGEMENT PLANE OF A DISTRIBUTED FIREWALL

FIG. 23

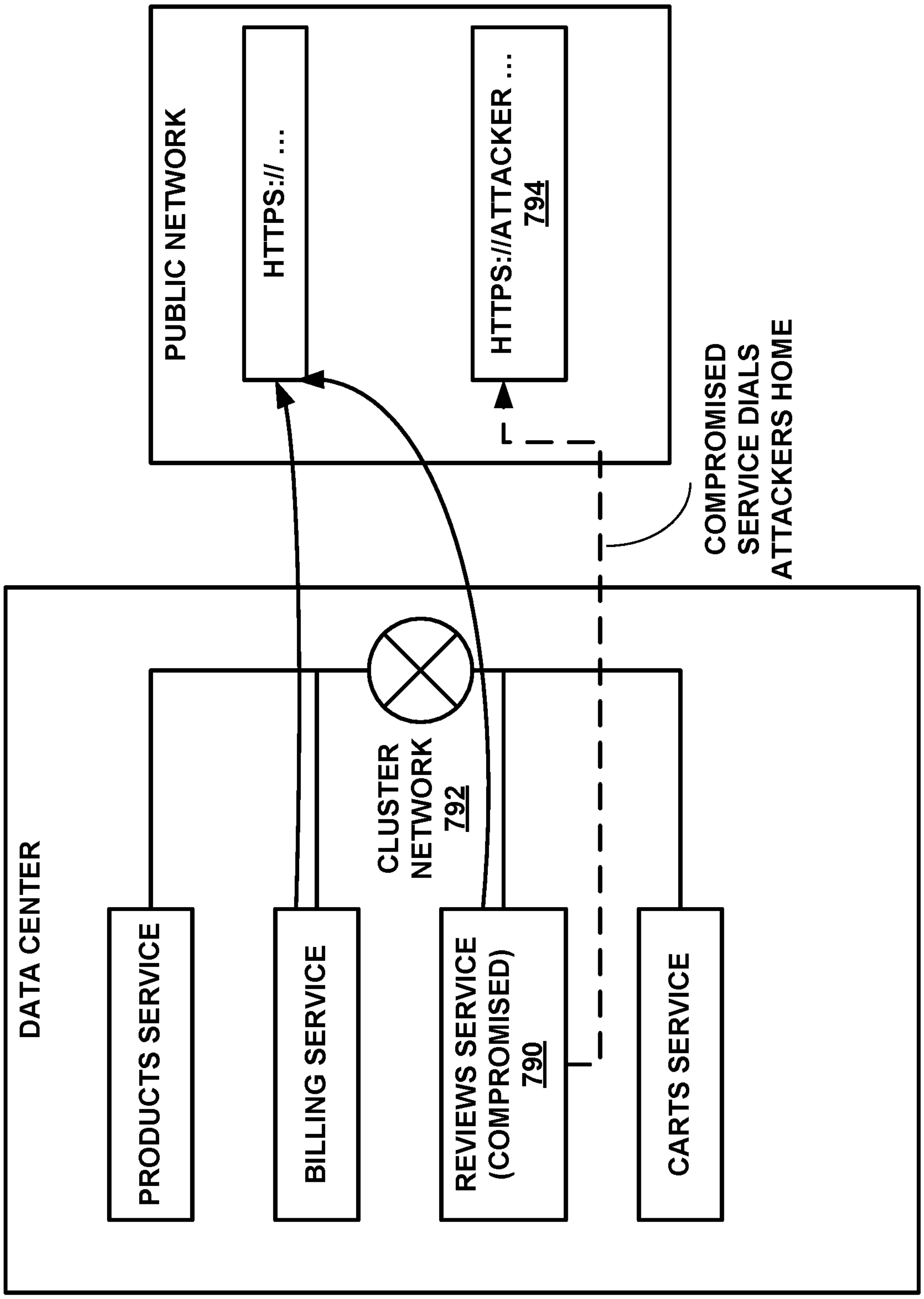
PUBLIC NETWORK
HTTPS:// ...
HTTPS://ATTACKER ...
794
COMPROMISED SERVICE DIALS ATTACKERS HOME
DATA CENTER
CLUSTER NETWORK
792
PRODUCTS SERVICE
BILLING SERVICE
REVIEWS SERVICE (COMPROMISED)
790
CARTS SERVICE

FIG. 24

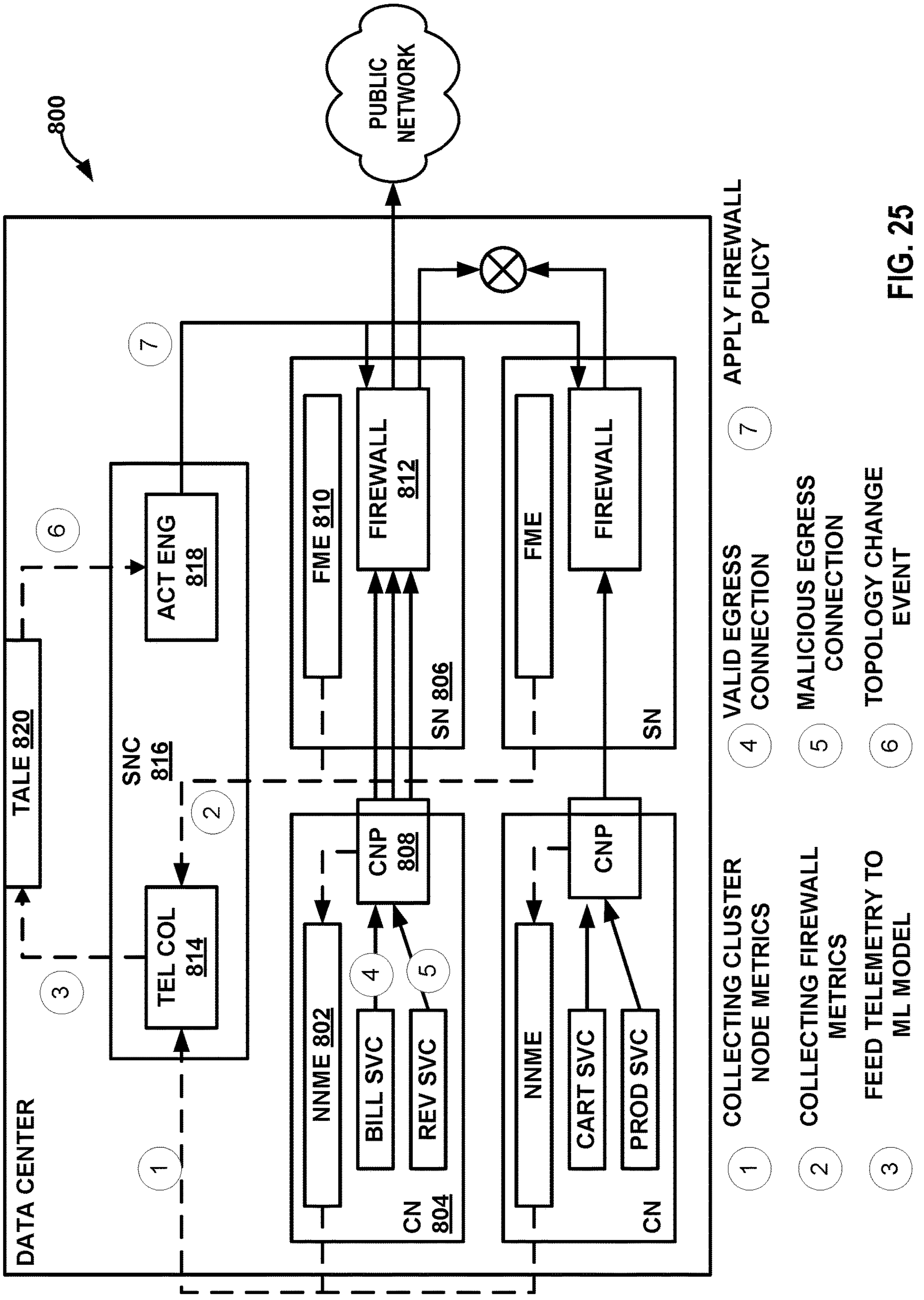
800
DATA CENTER
TALE 820
SNC 816
TEL COL 814
ACT ENG 818
PUBLIC NETWORK
FME 810
FIREWALL 812
SN 806
FME
FIREWALL
SN
NNME 802
BILL SVC
REV SVC
CNP 808
CN 804
NNME
CART SVC
PROD SVC
CNP
CN
1 COLLECTING CLUSTER NODE METRICS
2 COLLECTING FIREWALL METRICS
3 FEED TELEMETRY TO ML MODEL
4 VALID EGRESS CONNECTION
5 MALICIOUS EGRESS CONNECTION
6 TOPOLOGY CHANGE EVENT
7 APPLY FIREWALL POLICY

FIG. 25

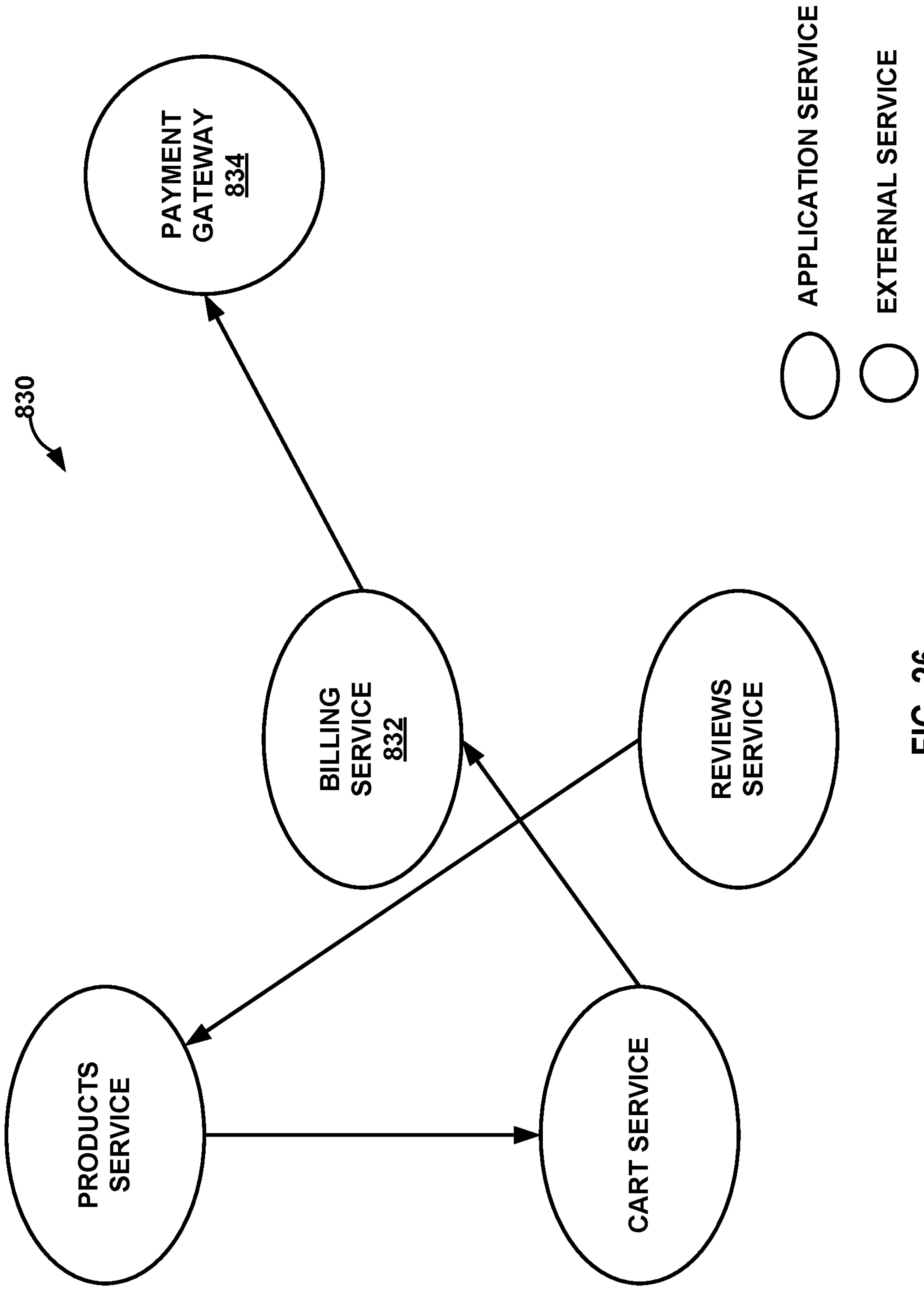
830
PAYMENT GATEWAY 834
BILLING SERVICE 832
REVIEWS SERVICE
PRODUCTS SERVICE
CART SERVICE
APPLICATION SERVICE
EXTERNAL SERVICE

FIG. 26

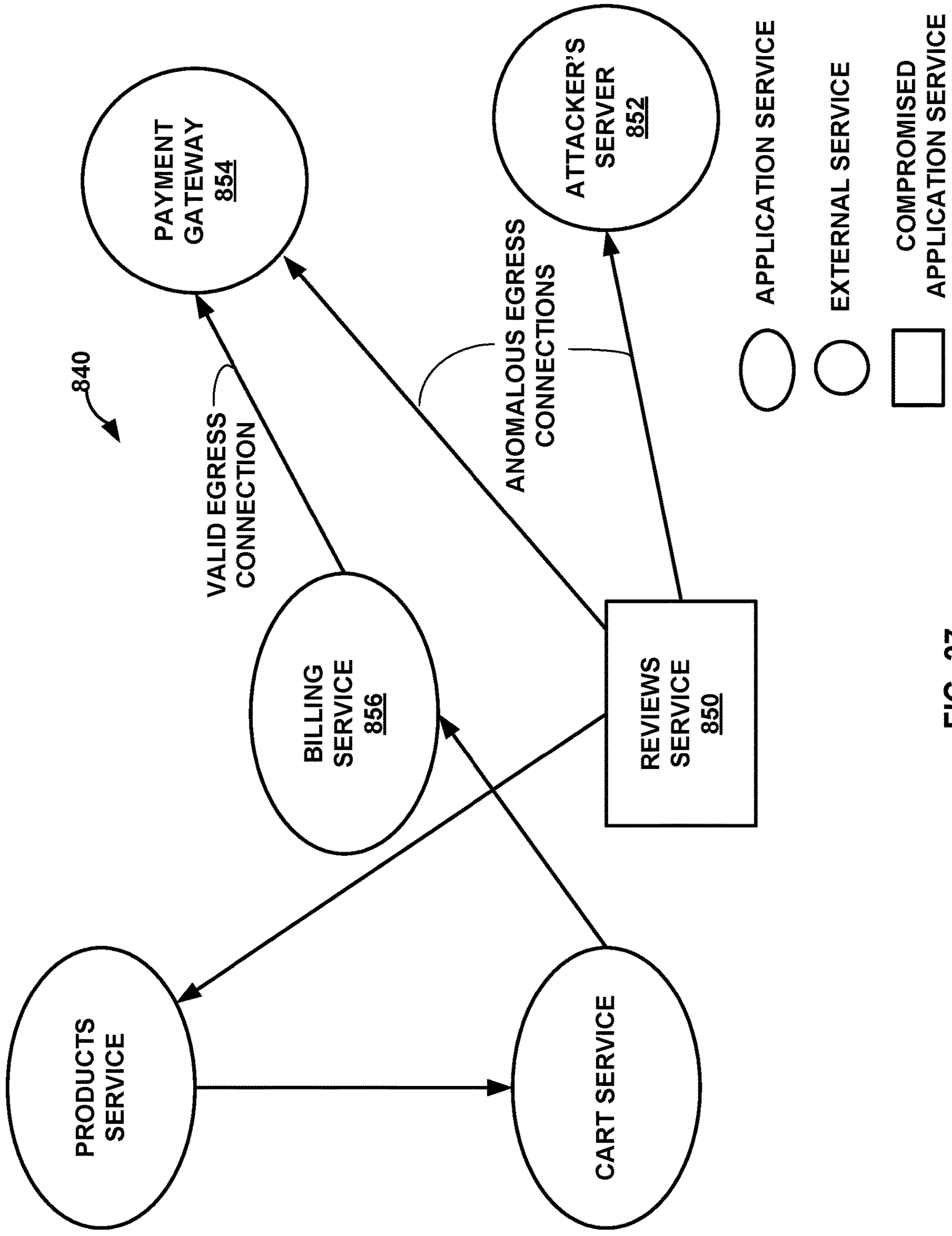
840
PAYMENT GATEWAY 854
ATTACKER'S SERVER 852
VALID EGRESS CONNECTION
ANOMALOUS EGRESS CONNECTIONS
BILLING SERVICE 856
REVIEWS SERVICE 850
PRODUCTS SERVICE
CART SERVICE
APPLICATION SERVICE
EXTERNAL SERVICE
COMPROMISED APPLICATION SERVICE

FIG. 27

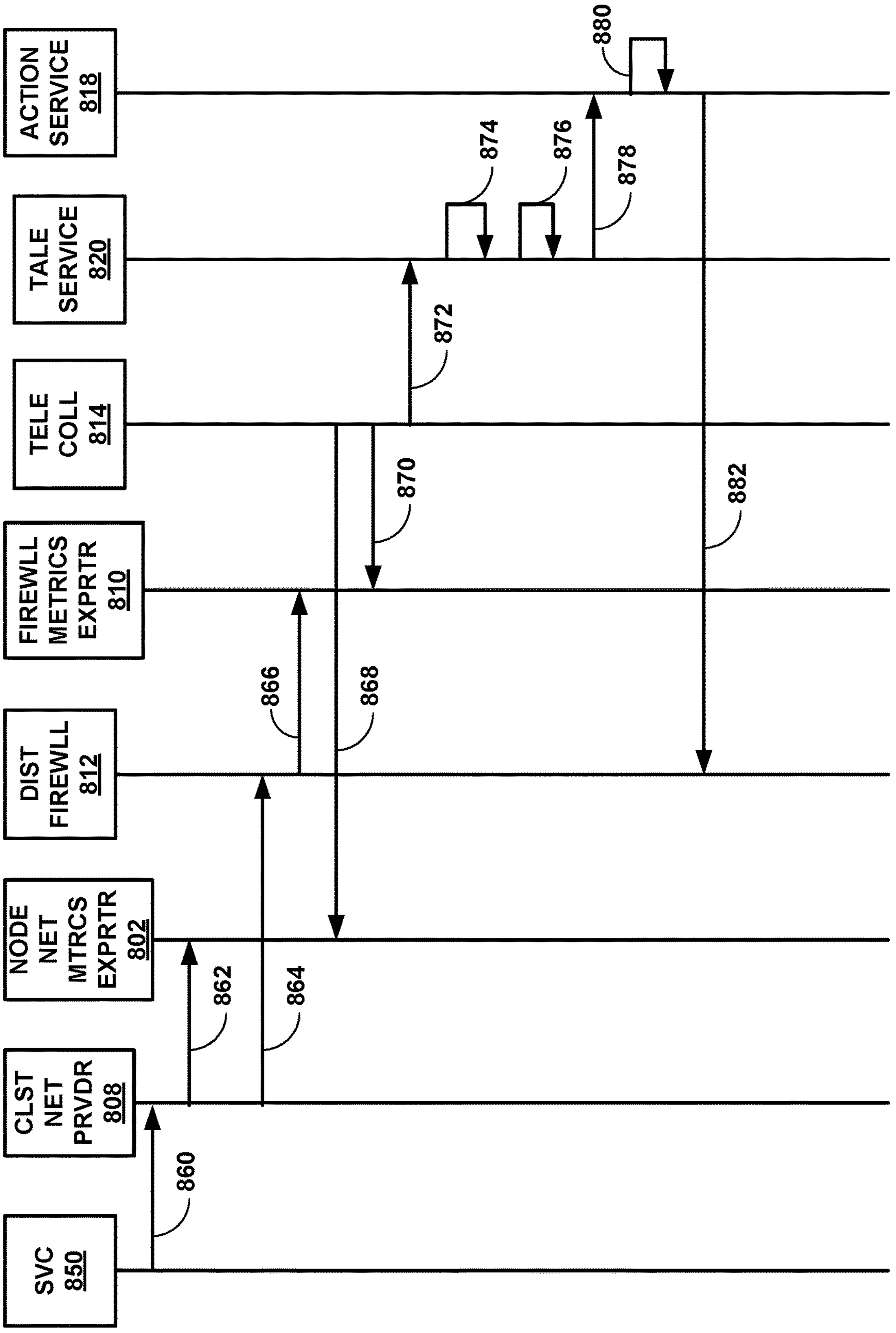
SVC 850
CLST NET PRVDR 808
NODE NET MTRCS EXPRTR 802
DIST FIREWLL 812
FIREWLL METRICS EXPRTR 810
TELE COLL 814
TALE SERVICE 820
ACTION SERVICE 818
860
862
864
866
868
870
872
874
876
878
880
882

FIG. 28

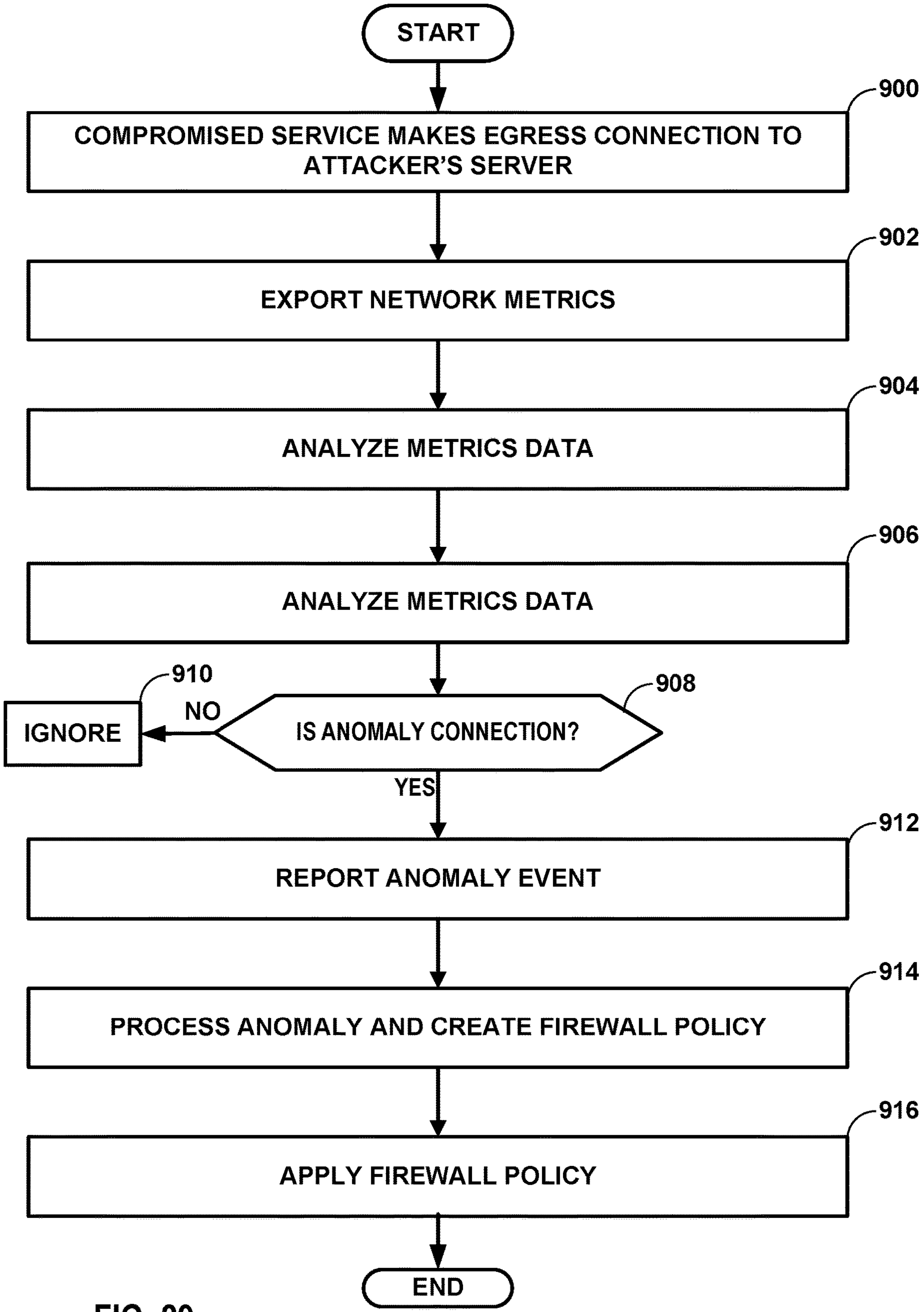
START
900
COMPROMISED SERVICE MAKES EGRESS CONNECTION TO ATTACKER'S SERVER
902
EXPORT NETWORK METRICS
904
ANALYZE METRICS DATA
906
ANALYZE METRICS DATA
910
IGNORE
NO
908
IS ANOMALY CONNECTION?
YES
912
REPORT ANOMALY EVENT
914
PROCESS ANOMALY AND CREATE FIREWALL POLICY
916
APPLY FIREWALL POLICY
END

FIG. 29

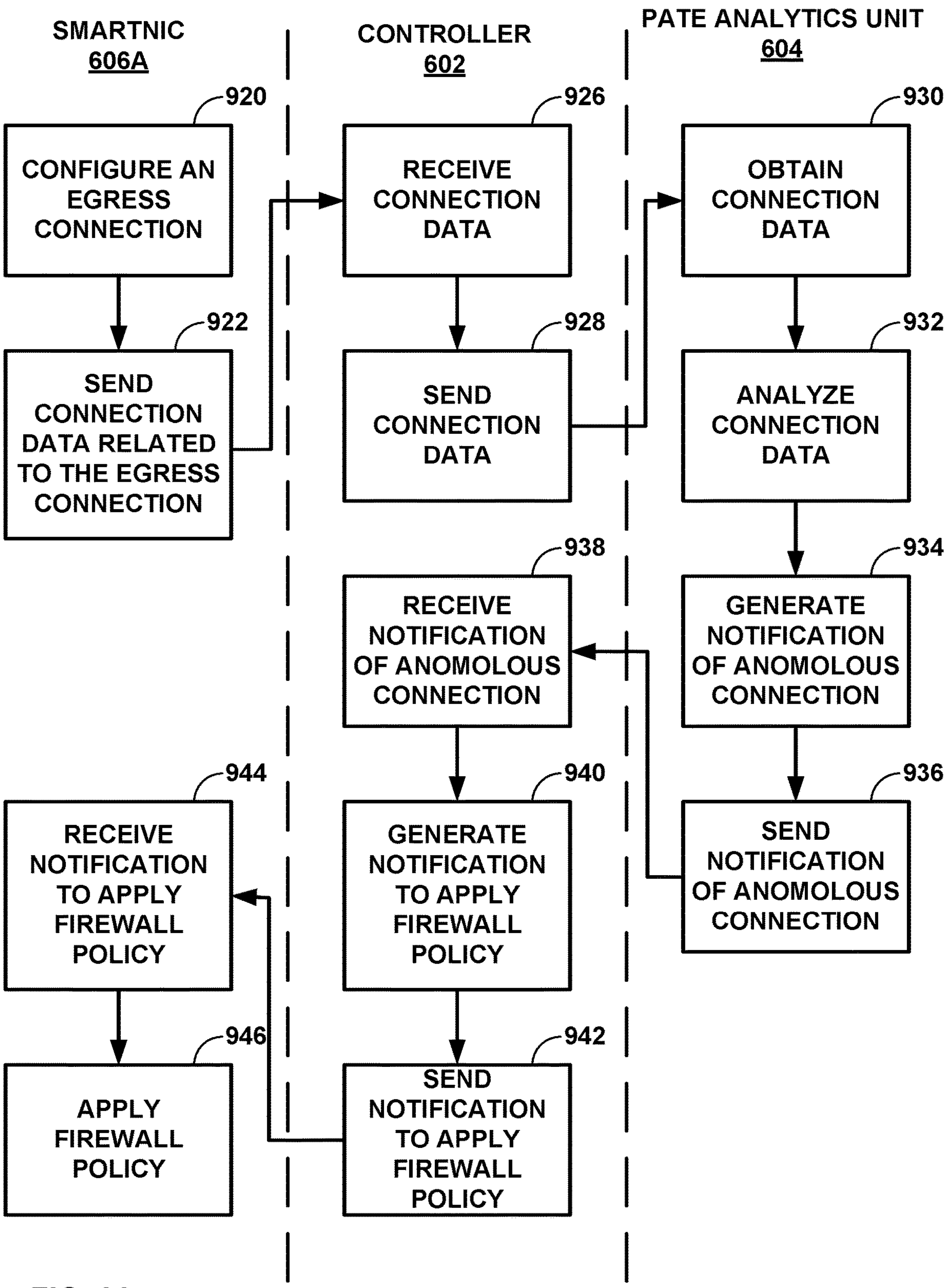
SMARTNIC
606A
CONTROLLER
602
PATE ANALYTICS UNIT
604
920
CONFIGURE AN EGRESS CONNECTION
922
SEND CONNECTION DATA RELATED TO THE EGRESS CONNECTION
926
RECEIVE CONNECTION DATA
928
SEND CONNECTION DATA
930
OBTAIN CONNECTION DATA
932
ANALYZE CONNECTION DATA
934
GENERATE NOTIFICATION OF ANOMOLOUS CONNECTION
936
SEND NOTIFICATION OF ANOMOLOUS CONNECTION
938
RECEIVE NOTIFICATION OF ANOMOLOUS CONNECTION
940
GENERATE NOTIFICATION TO APPLY FIREWALL POLICY
942
SEND NOTIFICATION TO APPLY FIREWALL POLICY
944
RECEIVE NOTIFICATION TO APPLY FIREWALL POLICY
946
APPLY FIREWALL POLICY

FIG. 30

SELF-CORRECTING SERVICE LEVEL AGREEMENT ENFORCER

This application claims priority to Indian Provisional Patent Application No. 202241069004, filed on Nov. 30, 2022, the entire contents of which is incorporated herein by reference.

TECHNICAL FIELD

The disclosure relates to computer networks.

BACKGROUND

In a typical cloud data center environment, there is a large collection of interconnected servers that provide computing and/or storage capacity to run various applications. For example, a data center may comprise a facility that hosts applications and services for subscribers, e.g., customers of a data center provider. The data center may, for example, host all of the infrastructure equipment, such as networking and storage systems, redundant power supplies, and environmental controls. In a typical data center, clusters of storage servers and application servers (compute nodes) are interconnected via a high-speed switch fabric provided by one or more tiers of physical network switches and routers. More sophisticated data centers provide infrastructure spread throughout the world with subscriber support equipment located in various physical hosting facilities.

The connectivity between the server and the switch fabric occurs at a hardware module called the network interface card (NIC). A conventional NIC includes an application-specific integrated circuit (ASIC) to perform packet forwarding, which includes some basic Layer 2/Layer 3 (L2/L3) functionality. In conventional NICs, the packet processing, policing and other advanced functionality, known as the "datapath," is performed by the host CPU, i.e., the CPU of the server that includes the NIC. As a result, the CPU resources in the server are shared by applications running on that server and also by datapath processing. For example, in a 4 core x86 server, one of the cores may be reserved for the datapath, leaving 3 cores (or 75% of CPU) for applications and the host operating system.

Some NIC vendors have begun including an additional processing unit in the NIC itself to offload at least some of the datapath processing from the host CPU to the NIC. The processing unit in the NIC may be, e.g., a multi-core ARM processor with some hardware acceleration provided by a Data Processing Unit (DPU), Field Programmable Gate Array (FPGA), and/or an ASIC. NICs that include such augmented datapath processing capabilities are typically referred to as SmartNICs.

SUMMARY

The emergence of cloud native applications is bringing additional complexity to the communication patterns within networks due to the highly distributed nature of cloud native applications and dynamic deployment conditions. Networks are now expected to be application-aware, which requires end nodes, such as servers, to participate in various networking tasks that traditionally are not performed by switches and/or routers. This has hastened the emergence of data processing units (DPUs) or smart network interface cards (SmartNICs) for performing different network services in an efficient manner. This disclosure presents a close-loop framework for implementing application-aware

network services using SmartNICs (also referred to herein as DPUs). In some examples, a machine learning model executing on a device and one or more SmartNICs may create a self-correcting network for management and observability of microservice-based applications. Along with, or through, the use of machine learning techniques, SmartNICs may perform continuous monitoring of application performance metrics and can take corrective actions to remediate security or performance issues in real-time (or near real-time).

Modern microservices-based applications may assume a network is a black box. These services may interact with each other using frameworks like Remote Procedure Call (e.g., gRPC) and Representational State Transfer (REST). These assumptions and interactions create an environment where the network is not aware of the applications that the network is transporting and vice versa, which may result in under-utilization of the capabilities of both the network and the microservices-based applications. Administrators may monitor applications and networking occurring within a network with different sets of tools, which my increase the cost of such monitoring and create unnecessary delays in responding to abnormalities, anomalies, or other issues discovered during such monitoring.

Network monitoring tools are generally not completely integrated with the rest of the infrastructure. In almost all monitoring architectures, switches and routers export telemetry data using, for example, Simple Network Management Protocol (SNMP) or a similar mechanism, so that monitoring software running on a server in the same network or in the cloud may analyze the telemetry data. These tools may identify some problems, but the tools have limited impact on the packet flows due the restricted telemetry data (e.g., network layer telemetry data) that the tools receive. Similarly, application monitoring requires complex software or sidecars running inside the service mesh using many system resources. As such, combining both network and application layer monitoring with a packet forwarding pipeline may be highly desirable.

Switches based on P4 (programming protocol-independent packet processors), like programmable pipelines, offered some hope of achieving the combination of network and application monitoring with the packet forwarding pipeline, but were unpopular. Network processors have the potential to solve this monitoring problem up to an extent, but network processors are usually present in the edge of the network, which may not be optimal. The emergence of DPUs and/or SmartNICs offer an opportunity to solve this monitoring problem by allowing monitoring software to be part of the packet forwarding flow without impacting latency and throughput. This emergence has enabled the ability to design a closed-loop architecture for implementing application-aware services such as application-aware threat detection and SLA enforcements using SmartNICs at a high scale in terms of bandwidth and latency. For example, SmartNICs may be used to monitor, detect, and neutralize threats in real-time and/or near-real time. Prior work has focused on using SmartNICs for accelerating workloads performance. The closed-loop framework disclosed herein enables use cases that may have been previously not possible. For example, existing learning-based solutions only monitor some part of the network traffic, like data going in and out of a datacenter. Due to this limitation, existing learning-based solutions may only enforce network policies at the network edge. With the popularity of public clouds, many enterprises share the same compute and network resources, requiring a greater need for policy enforcement inside a datacenter. The closed-loop system utilizing SmartNICs described in this disclosure may examine every packet generated in the datacenter resulting in a true application-aware policy enforcement system.

In this disclosure, the term SmartNIC is intended to cover the category of devices known as DPUs or Infrastructure Processing Units (IPUs). These SmartNICs are typically attached to servers in a PCIe card form factor. Each card may house a specialized silicon component (typically a single chip ASIC) which includes a set of processor cores and a specialized silicon complex which may be used to perform packet processing and security functions. One advantage of utilizing a SmartNIC is that a SmartNIC includes a hybrid architecture, e.g., provides for programmability through processing circuitry, such as ARM processor cores, and provides for specialized acceleration and offload functions through the ASIC. With the ability to introduce services on the ARM cores, servers may be completely isolated from the network and security services running on the SmartNIC.

In general, techniques are described for closed-loop application-aware network services including an edge services platform that leverages processing units of SmartNICs to augment the processing and networking functionality of a network of servers that include the SmartNICs. Features provided by the edge services platform may include, e.g., orchestration of SmartNICs; API driven deployment of services on SmartNICs; SmartNIC addition, deletion and replacement; monitoring of services (such as security services) and other resources on SmartNICs; and management of connectivity between various services running on the SmartNICs. More specifically, this disclosure describes techniques for dynamically generating and implementing firewall policies, dynamically correcting Service Level Agreement (SLA) issues, dynamically processing packets of a flow based on rankings, dynamically creating flow table entries, dynamically optimizing firewall policy searching, and dynamically accessing and/or mitigating egress traffic security issues, each using an edge services platform and one or more SmartNICs.

In one example, this disclosure describes a network system including processing circuitry; and one or more memories coupled to the processing circuitry and configured to store instructions which, when executed by the processing circuitry, cause the network system to: obtain telemetry data; determine, based on the telemetry data, that an application running on server processing circuitry does not meet at least one service level agreement (SLA) requirement, the server processing circuitry not including processing circuitry resident on a network interface card (NIC); and based on the application not meeting the at least one SLA requirement, determine to offload at least one component of the application from the server processing circuitry to the processing circuitry resident on the NIC.

In another example, this disclosure describes a method including obtaining telemetry data; determining, based the telemetry data, that an application running on server processing circuitry does not meet at least one service level agreement (SLA) requirement, the server processing circuitry not including processing circuitry resident on a network interface card (NIC); and based on the application not meeting the at least one SLA requirement, determining to offload at least one component of the application from the server processing circuitry to the processing circuitry resident on the NIC.

In yet another example, this disclosure describes computer-readable storage media storing instructions, which, when executed, cause processing circuitry to: obtain telemetry data; determine, based on the telemetry data, that an application running on server processing circuitry does not meet at least one service level agreement (SLA) requirement, the server processing circuitry not including processing circuitry resident on a network interface card (NIC); and based on the application not meeting the at least one SLA requirement, determine to offload at least one component of the application from the server processing circuitry to the processing circuitry resident on the NIC.

The details of one or more examples of this disclosure are set forth in the accompanying drawings and the description below. Other features, objects, and advantages will be apparent from the description and drawings, and from the claims.

BRIEF DESCRIPTION OF DRAWINGS

FIG. **1** is a block diagram illustrating an example network system having a data center in which examples of the techniques described herein may be implemented.

FIG. **2** is a block diagram illustrating an example computing device that uses a network interface card having a separate processing unit, to perform services managed by an edge services platform according to techniques described herein.

FIG. **3** is a conceptual diagram illustrating a data center with servers that each include a network interface card having a separate processing unit, controlled by an edge services platform, according to techniques of this disclosure.

FIG. **4** is a block diagram illustrating an example computing device that uses a network interface card having a separate processing unit, to perform services managed by an edge services platform according to techniques described herein.

FIG. **5** a block diagram illustrating an example system, according to techniques of this disclosure.

FIG. **6** is a conceptual diagram illustrating an example close-loop architecture for application-aware services in Smart network interface controllers (SmartNICs) according to one or more aspects of this disclosure.

FIG. **7** is a block diagram illustrating an example telemetry collector architecture according to one or more aspects of this disclosure.

FIG. **8** is a block diagram illustrating an example action unit architecture according to one or more aspects of this disclosure.

FIG. **9** is a block diagram illustrating an example performance analysis and troubleshooting engine (PATE) service unit architecture according to one or more aspects of this disclosure.

FIG. **10** is a block diagram illustrating an example anomaly detection pipeline according to one or more aspects of this disclosure.

FIGS. **11**A and **11**B are conceptual diagrams illustrating example attacker attempts to block the service discovery control plane functionality of a service mesh according to one or more aspects of this disclosure.

FIG. **12** is a graphical diagram illustrating example anomaly mitigation time as the number of attacks are increased according to one or more aspects of this disclosure.

FIG. **13** is a table illustrating example anomaly detection for service-discovery-dns-count-per-minute metric according to one or more aspects of this disclosure.

FIG. **14** is a flow diagram illustrating example anomaly detection according to one or more aspects of this disclosure.

FIG. **15** is a conceptual diagram illustrating example application communication topology before and after an attack according to one or more aspects of this disclosure.

FIG. **16** is a conceptual diagram illustrating example auto-Service Level Agreement (SLA) enforcement techniques according to one or more aspects of this disclosure.

FIG. **17** is a flow diagram illustrating example offloading techniques according to one or more aspects of this disclosure.

FIG. **18** is a conceptual diagram illustrating example self-learning flow priority techniques according to one or more aspects of this disclosure.

FIG. **19** is a flow diagram illustrating example flow ranking techniques according to one or more aspects of this disclosure.

FIG. **20** is a flow diagram illustrating example packet processing techniques of a firewall service according to one or more aspects of this disclosure.

FIG. **21** is a flow diagram illustrating example policy table population techniques according to one or more aspects of this disclosure.

FIG. **22** is a block diagram illustrating an example firewall policy optimizer according to one or more aspects of this disclosure.

FIG. **23** is a flow diagram illustrating example techniques for reducing a number of firewall polices distributed to nodes of a distributed firewall according to one or more aspects of this disclosure.

FIG. **24** is a conceptual diagram illustrating example egress traffic-based attacks according to one or more aspects of this disclosure.

FIG. **25** is a conceptual diagram illustrating an example self-learning egress traffic controller according to one or more aspects of this disclosure.

FIG. **26** is a conceptual diagram illustrating example an application knowledge graph before egress attacks according to one or more aspects of this disclosure.

FIG. **27** is a conceptual diagram illustrating example updated knowledge graph according to one or more aspects of this disclosure.

FIG. **28** is a sequence diagram illustrating example techniques for configuring a firewall policy to mitigate an egress attack according to one or more aspects of this disclosure.

FIG. **29** is a flow diagram illustrating example techniques for configuring a firewall policy to mitigate an egress attack according to one or more aspects of this disclosure.

FIG. **30** is a flow diagram illustrating example techniques for responding to malicious egress connections according to one or more aspects of this disclosure.

Like reference characters denote like elements throughout the description and figures.

DETAILED DESCRIPTION

FIG. **1** is a block diagram illustrating an example network system **8** having a data center **10** in which examples of the techniques described herein may be implemented. In general, data center **10** provides an operating environment for applications and services for customer sites **11** having one or more customer networks coupled to data center **10** by a service provider network **7**. Data center **10** may, for example, host infrastructure equipment, such as networking and storage systems, redundant power supplies, and environmental controls. Service provider network **7** is coupled to a public network **4**. Public network **4** may represent one or more networks administered by other providers and may thus form part of a large-scale public network infrastructure,

e.g., the Internet. For instance, public network **4** may represent a local area network (LAN), a wide area network (WAN), the Internet, a virtual LAN (VLAN), an enterprise LAN, a layer 3 virtual private network (VPN), an Internet Protocol (IP) intranet operated by the service provider that operates service provider network **7**, an enterprise IP network, or some combination thereof.

Although customer sites **11** and public network **4** are illustrated and described primarily as edge networks of service provider network **7**, in some examples, one or more of customer sites **11** and public network **4** are tenant networks within data center **10** or another data center. For example, data center **10** may host multiple tenants (customers) each associated with one or more virtual private networks (VPNs). Each of the VPNs may implement one of customer sites **11**.

Service provider network **7** offers packet-based connectivity to attached customer sites **11**, data center **10**, and public network **4**. Service provider network **7** may represent a network that is operated (and potentially owned) by a service provider to interconnect a plurality of networks. Service provider network **7** may implement Multi-Protocol Label Switching (MPLS) forwarding and, in such instances, may be referred to as an MPLS network or MPLS backbone. In some instances, service provider network **7** represents a plurality of interconnected autonomous systems, such as the Internet, that offers services from one or more service providers.

In some examples, data center **10** may represent one of many geographically distributed network data centers. As illustrated in the example of FIG. **1**, data center **10** may be a facility that provides network services for customers. A customer of the service provider may be a collective entity such as enterprises and governments or individuals. For example, a network data center may host web services for several enterprises and end users. Other exemplary services may include data storage, virtual private networks, traffic engineering, file service, data mining, scientific- or super-computing, and so on. Although illustrated as a separate edge network of service provider network **7**, elements of data center **10**, such as one or more physical network functions (PNFs) or virtualized network functions (VNFs), may be included within the service provider network **7** core.

In this example, data center **10** includes storage and/or compute servers interconnected via switch fabric **14** provided by one or more tiers of physical network switches and routers, with servers **12**A-**12**X (herein, "servers **12**") depicted as coupled to top-of-rack (TOR) switches **16**A-**16**N. This disclosure may refer to TOR switches **16**A-**16**N collectively, as "TOR switches **16**." TOR switches **16** may be network devices that provide layer 2 (MAC) and/or layer 3 (e.g., IP) routing and/or switching functionality.

Servers **12** may also be referred to herein as "hosts" or "host devices." Data center **10** may include many additional servers coupled to other TOR switches **16** of the data center **10**. In the example of FIG. **1**, servers **12**A and **12**X are directly coupled to TOR switches **16**, and servers **12**B, **12**C, and **12**D are not directly coupled to TOR switches **16** in the illustrated example. Servers **12**B, **12**C, and **12**D may reach TOR switches **16** and IP fabric **20** via servers **12**A or **12**X, as described in further detail below.

Switch fabric **14** in the illustrated example includes interconnected TOR switches **16** (or other "leaf" switches) coupled to a distribution layer of chassis switches **18**A-**18**M (collectively, "chassis switches **18**"). Chassis switches may also be referred to as "spine" or "core" switches. Although not shown in the example of FIG. **1**, data center **10** may also include one or more non-edge switches, routers, hubs, gateways, security devices such as firewalls, intrusion detection, and/or intrusion prevention devices, servers, computer terminals, laptops, printers, databases, wireless mobile devices such as cellular phones or personal digital assistants, wireless access points, bridges, cable modems, application accelerators, and/or other network devices.

In some examples, TOR switches **16** and chassis switches **18** provide servers **12** with redundant (e.g., multi-homed) connectivity to IP fabric **20** and service provider network **7**. Chassis switches **18** aggregate traffic flows and provide connectivity between TOR switches **16**. TOR switches **16** and chassis switches **18** may each include one or more processors and a memory and can execute one or more software processes. Chassis switches **18** are coupled to IP fabric **20**, which may perform layer 3 routing to route network traffic between data center **10** and customer sites **11** via service provider network **7**. The switching architecture of data center **10** shown in FIG. **1** is merely an example. Other switching architectures may have more or fewer switching layers, for instance. TOR switches **16** and chassis switches **18** may each include physical network interfaces.

In this disclosure, the terms "packet flow," "traffic flow," or simply "flow" each refer to a set of packets originating from a particular source device or endpoint and sent to a particular destination device or endpoint. A single flow of packets may be identified by the 5-tuple: <source network address, destination network address, source port, destination port, protocol>, for example. This 5-tuple generally identifies a packet flow to which a received packet corresponds. An n-tuple refers to any n items drawn from the 5-tuple. For example, a 2-tuple for a packet may refer to the combination of <source network address, destination network address> or <source network address, source port> for the packet. The term "source port" refers to a transport layer (e.g., transmission control protocol (TCP)/user datagram protocol (UDP)) port. A "port" may refer to a physical network interface of a NIC.

Each of servers **12** may be a compute node, an application server, a storage server, or other type of server. For example, each of servers **12** may represent a computing device, such as an x86 processor-based server, configured to operate according to techniques described herein. Servers **12** may provide Network Function Virtualization Infrastructure (NFVI) for a Network Function Virtualization (NFV) architecture.

Servers **12** may host endpoints for one or more virtual networks that operate over the physical network represented in FIG. **1** by IP fabric **20** and switch fabric **14**. Endpoints may include one or more virtual network endpoints, e.g., virtual machines, containerized applications (e.g., of orchestration platforms including Kubernetes, Docker swarm, Mesos/Marathon, OpenShift, OpenStack, VMWare, and Amazon ECS), or applications executing natively on the operating system or bare metal. Containerization is a virtualization scheme based on operation system-level virtualization. Like a virtual machine, each container is virtualized and may remain isolated from one another and from the host machine. However, unlike a virtual machine, each container may omit an individual operating system and provide only an application suite and application-specific libraries. In general, a container is executed by the host machine as an isolated user-space instance and may share an operating system and common libraries with other containers executing on the host machine. Containers may be managed as groups of logically-related elements (sometimes referred to as "pods" for some orchestration platforms, e.g., Kubernetes). Although described primarily with respect to a data center-based switching network, other physical networks, such as service provider network **7**, may underlay the one or more virtual networks.

Each of servers **12** includes at least one network interface card (NIC) of NICs **13**A-**13**X (collectively, "NICs **13**"). For example, server **12**A includes NIC **13**A. Each of NICs **13** includes at least one port. Each of NICs **13** may send and receive packets over one or more communication links coupled to the ports of the NIC.

In some examples, each of NICs **13** provides one or more virtual hardware components for virtualized input/output (I/O)). A virtual hardware component for virtualized I/O may be a virtualization of a physical NIC **13** (the "physical function"). For example, in Single Root I/O Virtualization (SR-IOV), which is described in the Peripheral Component Interface Special Interest Group SR-IOV specification, the Peripheral Component Interface (PCI) express (PCIe) Physical Function of the network interface card (or "network adapter") is virtualized to present one or more virtual network interface cards as "virtual functions" for use by respective endpoints executing on the server **12**. In this way, the virtual network endpoints may share the same PCIe physical hardware resources and the virtual functions are examples of virtual hardware components. As another example, one or more servers **12** may implement Virtio, a para-virtualization framework available, e.g., for the Linux Operating System, that provides emulated NIC functionality as a type of virtual hardware component. As another example, one or more servers **12** may implement Open vSwitch to perform distributed virtual multilayer switching between one or more virtual NICs (vNICs) for hosted virtual machines, where such vNICs may also represent a type of virtual hardware component. In some instances, the virtual hardware components are virtual I/O (e.g., NIC) components. In some instances, the virtual hardware components are SR-IOV virtual functions and may provide SR-IOV with Data Plane Development Kit (DPDK)-based direct process user space access.

In some examples, including the example of FIG. **1**, one or more of NICs **13** include multiple ports. NICs **13** may be connected to one another via ports of NICs **13** and communications links to form a NIC fabric **23** having a NIC fabric topology. NIC fabric **23** is the collection of NICs **13** connected to at least one other of NICs **13** and the communications links coupling NICs **13** to one another.

NICs **13**A-**13**X include corresponding processing circuitry, such as processing units **25**A-**25**X (collectively, "processing units **25**"). Processing units **25** may offload aspects of the datapath from CPUs of servers **12**. One or more of processing units **25** may be a multi-core ARM processor with hardware acceleration provided by a Data Processing Unit (DPU), a Field Programmable Gate Array (FPGA), and/or an Application Specific Integrated Circuit (ASIC). Because NICs **13** include processing units **25**, NICs **13** may be referred to as "SmartNICs" or "GeniusNICs."

In accordance with various aspects of the techniques of this disclosure, an edge services platform uses processing units **25** of NICs **13** to augment the processing and networking functionality of switch fabric **14** and/or servers **12** that include NICs **13**. In the example of FIG. **1**, network system **8** includes an edge services controller **28**. This disclosure may also refer to an edge services controller, such as edge services controller **28**, as an edge services platform controller.

Edge services control **28** may manage the operations of the edge services platform within NIC **13**s in part by orchestrating services performed by processing units **25**; orchestrating API driven deployment of services on NICs **13**; orchestrating NIC **13** addition, deletion, and replacement within the edge services platform; monitoring of services and other resources on NICs **13**; and/or management of connectivity between various services **133** running on the NICs **13**. Edge services controller **28** may include one or more computing devices, such as server devices, personal computers, intermediate network devices, or the like.

Edge services controller **28** may communicate information describing services available on NICs **13**, a topology of NIC fabric **23**, or other information about the edge services platform to an orchestration system (not shown) or a controller **24**. Example orchestration systems include OpenStack, vCenter by VMWARE, or System Center by Microsoft Corporation of Redmond, Washington. Example controllers include a controller for Contrail by JUNIPER NETWORKS or Tungsten Fabric. Controller **24** may be a network fabric manager. Additional information regarding a controller **24** operating in conjunction with other devices of data center **10** or other software-defined network is found in International Application Number PCT/US2013/044378, filed Jun. 5, 2013, and entitled "PHYSICAL PATH DETERMINATION FOR VIRTUAL NETWORK PACKET FLOWS;" and in U.S. Pat. No. 9,571,394, filed Mar. 26, 2014, and entitled "TUNNELED PACKET AGGREGATION FOR VIRTUAL NETWORKS," each of which is incorporated by reference as if fully set forth herein.

In some examples, edge services controller **28** programs processing units **25** of NICs **13** to route data packets along data paths through NIC fabric **23**, e.g., based on applications (services) associated with the data packets. Routing data packets along data paths through NIC fabric **23** may avoid overloading individual NICs in NIC fabric **23** when multiple services on a pair of hosts are communicating with each other. For example, edge services controller **28** may manage data packet routing in NIC fabric **23**. As shown in FIG. **1**, NIC fabric **23** comprises a plurality of NICs **13** coupled by communication links in a NIC fabric topology. In this example, edge services controller **28** may receive resource availability values from NICs **13**. Edge services controller **28** may determine a data path for data packets of a flow transported using a protocol from a source NIC to a destination NIC via a NIC set that comprises at least one NIC. NICs **13** include the source NIC, the destination NIC, and the NIC set. As part of determining the data path, edge services controller **28** may select the NIC set based on the resource availability values. Edge services controller **28** may transmit, to the source NIC and to each NIC in the NIC set, data path data to cause the source NIC and each NIC in the NIC set to identify the data packets of the flow using an identifier of the protocol and to transmit the data packets of the flow from the source NIC to the destination NIC via the data path. Edge services controller **28** may establish multiple data paths in this manner. Unlike in a conventional data center fabric, servers **12** may thus exchange packets directly, rather than via a separate switching device (such as chassis switches **18**). The above may be considered a form of service load balancing.

The example system of FIG. **1** may form a closed-loop framework for implementing application-aware network services using SmartNICs, such as NICs **13**, as further described below.

FIG. **2** is a block diagram illustrating an example computing device **200** that uses a NIC **230** having a separate processing unit **25**, to perform services managed by an edge services platform according to techniques described herein.

For example, NIC **230** may implement a portion of a distributed firewall service, implement portions of a service executing on a server, such as one of servers **12** of FIG. **1**, or the like. Computing device **200** of FIG. **2** may represent a real or virtual server and may represent an example instance of any of servers **12** of FIG. **1**. In the example of FIG. **2**, computing device **200** includes a bus **242** that couples hardware components of the hardware environment of computing device **200**. Specifically, in the example of FIG. **2**, bus **242** couples a Single Route Input/Output Virtualization (SR-IOV)-capable NIC **230**, a storage disk **246**, and a microprocessor **210**. In some examples, a front-side bus couples microprocessor **210** and memory device **244**. In some examples, bus **242** couples memory device **244**, microprocessor **210**, and NIC **230**. Bus **242** may represent a PCIe bus. In some examples, a direct memory access (DMA) controller may control DMA transfers among components coupled to bus **242**. In some examples, components coupled to bus **242** control DMA transfers among components coupled to bus **242**.

Microprocessor **210** may include one or more processors each including an independent execution unit ("processing core") to perform instructions that conform to an instruction set architecture. Execution units may be implemented as separate integrated circuits (ICs) or may be combined within one or more multi-core processors (or "many-core" processors) that are each implemented using a single IC (i.e., a chip multiprocessor).

Disk **246** represents computer readable storage media that includes volatile and/or non-volatile, removable and/or non-removable media implemented in any method or technology for storage of information such as processor-readable instructions, data structures, program modules, or other data. Computer readable storage media includes, but is not limited to, random access memory (RAM), read-only memory (ROM), EEPROM, flash memory, CD-ROM, digital versatile discs (DVD) or other optical storage, magnetic cassettes, magnetic TALE, magnetic disk storage or other magnetic storage devices, or any other medium that can be used to store the desired information and that can be accessed by microprocessor **210**.

Memory device **244** includes one or more computer-readable storage media, which may include random-access memory (RAM) such as various forms of dynamic RAM (DRAM), e.g., DDR2/DDR3 SDRAM, or static RAM (SRAM), flash memory, or any other form of fixed or removable storage medium that can be used to carry or store desired program code and program data in the form of instructions or data structures and that can be accessed by a computer. Memory device **244** provides a physical address space composed of addressable memory locations.

Network interface card (NIC) **230** includes one or more interfaces **232** configured to exchange packets using links of an underlying physical network. Interfaces **232** may include a port interface card having one or more network ports. NIC **230** also include an on-card memory **227** to, e.g., store packet data. Direct memory access transfers between NIC **230** and other devices coupled to bus **242** may read/write from/to the memory **227**.

Memory device **244**, NIC **230**, disk **246**, and microprocessor **210** provide an operating environment for a software stack that executes a hypervisor **214** and one or more virtual machines **228** managed by hypervisor **214**. In general, a virtual machine provides a virtualized/guest operating system for executing applications in an isolated virtual environment. Because a virtual machine is virtualized from physical hardware of the host server, executing applications are isolated from both the hardware of the host and other virtual machines. Computing device **200** executes hypervisor **214** to manage virtual machines **228**. Example hypervisors include Kernel-based Virtual Machine (KVM) for the Linux kernel, Xen, ESXi available from VMWARE, Windows Hyper-V available from MICROSOFT, and other open-source and proprietary hypervisors. Hypervisor **214** may represent a virtual machine manager (VMM). Virtual machines **228** may host one or more applications, such as virtual network function instances. In some examples, a virtual machine **228** may host one or more VNF instances, where each of the VNF instances is configured to apply a network function to packets.

An alternative to virtual machines is the virtualized container, such as those provided by the open-source DOCKER Container application. Like a virtual machine, each container is virtualized and may remain isolated from the host machine and other containers. However, unlike a virtual machine, each container may omit an individual operating system and provide only an application suite and application-specific libraries. A container is executed by the host machine as an isolated user-space instance and may share an operating system and common libraries with other containers executing on the host machine. Thus, containers may require less processing power, storage, and network resources than virtual machines. As used herein, containers may also be referred to as virtualization engines, virtual private servers, silos, or jails. In some instances, the techniques described herein with respect to containers and virtual machines or other virtualization components.

While virtual network endpoints in FIG. **2** are illustrated and described with respect to virtual machines, other operating environments, such as containers (e.g., a DOCKER container) may implement virtual network endpoints. An operating system kernel (not shown in FIG. **2**) may execute in kernel space and may include, for example, a Linux, Berkeley Software Distribution (BSD), another Unix-variant kernel, or a Windows server operating system kernel, available from MICROSOFT.

Hypervisor **214** includes a physical driver **225** to use a physical function provided by NIC **230**. In some cases, NIC **230** may also implement SR-IOV to enable sharing the physical network function (I/O) among virtual machines **224**. Each port of NIC **230** may be associated with a different physical function. The shared virtual devices, also known as virtual functions, provide dedicated resources such that each of virtual machines **228** (and corresponding guest operating systems) may access dedicated resources of NIC **230**, which therefore appears to each of virtual machines **228** as a dedicated NIC. Virtual functions may be lightweight PCIe functions that share physical resources with the physical function and with other virtual functions. NIC **230** may have thousands of available virtual functions according to the SR-IOV standard, but for I/O-intensive applications the number of configured virtual functions is typically much smaller.

Virtual machines **228** include respective virtual NICs **229** presented directly into the virtual machine **228** guest operating system, thereby offering direct communication between NIC **230** and virtual machines **228** via bus **242**, using the virtual function assigned for the virtual machine. This may reduce hypervisor **214** overhead involved with software-based, VIRTIO and/or vSwitch implementations in which a memory address space of hypervisor **214** within memory device **244** stores packet data and because copying packet data from NIC **230** to the memory address space of hypervisor **214** and from the memory address space of

hypervisor **214** to memory address spaces of virtual machines **228** consumes cycles of microprocessor **210**.

NIC **230** may further include a hardware-based Ethernet bridge **234**. Ethernet bridge **234** may be an example of an embedded switch. Ethernet bridge **234** may perform layer 2 forwarding between virtual functions and physical functions of NIC **230**. Thus, in some cases, Ethernet bridge **234** provides hardware acceleration, via bus **242**, of inter-virtual machine **228** packet forwarding and hardware acceleration of packet forwarding between hypervisor **214** and any of virtual machines **228**. Hypervisor **214** may access the physical function via physical driver **225**. Ethernet bridge **234** may be physically separate from processing unit **25**.

Computing device **200** may be coupled to a physical network switch fabric that includes an overlay network that extends a switch fabric from physical switches to software or "virtual" routers of physical servers coupled to the switch fabric, including virtual router **220**. Virtual routers may be processes or threads, or a component thereof, executed by the physical servers, e.g., servers **12** of FIG. **1**, that dynamically create and manage one or more virtual networks usable for communication between virtual network endpoints. In one example, virtual routers implement each virtual network using an overlay network, which provides the capability to decouple an endpoint's virtual address from a physical address (e.g., IP address) of the server on which the endpoint is executing. Each virtual network may use its own addressing and security scheme and may be viewed as orthogonal from the physical network and its addressing scheme. Various techniques may be used to transport packets within and across virtual networks over the physical network. At least some functions of the virtual router may be performed as one of services **233** or fabric service **235**. In the example of FIG. **2**, virtual router **220** executes within hypervisor **214** that uses physical function for I/O, but virtual router **220** may execute within a hypervisor, a host operating system, a host application, one of virtual machines **228**, and/or processing unit **25** of NIC **230**.

In general, each virtual machine **228** may be assigned a virtual address for use within a corresponding virtual network, where each of the virtual networks may be associated with a different virtual subnet provided by virtual router **220**. A virtual machine **228** may be assigned its own virtual layer three (L3) IP address, for example, for sending and receiving communications but may be unaware of an IP address of the computing device **200** on which the virtual machine is executing. In this way, a "virtual address" is an address for an application that differs from the logical address for the underlying, physical computer system, e.g., computing device **200**.

In one implementation, computing device **200** includes a virtual network (VN) agent (not shown) that controls the overlay of virtual networks for computing device **200** and that coordinates the routing of data packets within computing device **200**. In general, a VN agent communicates with a virtual network controller for the multiple virtual networks, which generates commands to control routing of packets. A VN agent may operate as a proxy for control plane messages between virtual machines **228** and the virtual network controller, such as controller **24** (FIG. **1**). For example, a virtual machine may request to send a message using its virtual address via the VN agent, and VN agent may in turn send the message and request that a response to the message be received for the virtual address of the virtual machine that originated the first message. In some cases, a virtual machine **228** may invoke a procedure or function call presented by an application programming interface of VN agent, and the VN agent may handle encapsulation of the message as well, including addressing.

In one example, network packets, e.g., layer three (L3) IP packets or layer two (L2) Ethernet packets generated or consumed by the instances of applications executed by virtual machine **228** within the virtual network domain, may be encapsulated in another packet (e.g., another IP or Ethernet packet) that is transported by the physical network. The packet transported in a virtual network may be referred to herein as an "inner packet" while the physical network packet may be referred to herein as an "outer packet" or a "tunnel packet." Encapsulation and/or de-capsulation of virtual network packets within physical network packets may be performed by virtual router **220**. This functionality is referred to herein as tunneling and may be used to create one or more overlay networks. Besides IPinIP, other example tunneling protocols that may be used include IP over Generic Route Encapsulation (GRE), Virtual Extensible Local Area Network (VXLAN), Multiprotocol Label Switching (MPLS) over GRE (MPLSoGRE), MPLS over User Datagram Protocol (UDP) (MPLSoUDP), etc.

As noted above, a virtual network controller may provide a logically centralized controller for facilitating operation of one or more virtual networks. The virtual network controller may, for example, maintain a routing information base, e.g., one or more routing tables that store routing information for the physical network as well as one or more overlay networks. Virtual router **220** of hypervisor **214** implements a network forwarding table (NFT) **222**A-**222**N for N virtual networks for which virtual router **220** operates as a tunnel endpoint. In general, each NFT **222** stores forwarding information for the corresponding virtual network and identifies where data packets are to be forwarded and whether the packets are to be encapsulated in a tunneling protocol, such as with a tunnel header that may include one or more headers for different layers of the virtual network protocol stack. Each of NFTs **222** may be an NFT for a different routing instance (not shown) implemented by virtual router **220**.

In accordance with techniques of this disclosure, edge services controller **28** (FIG. **1**) uses processing unit **25** of NIC **230** to augment the processing and networking functionality of computing device **200**. Processing unit **25** includes processing circuitry **231** to execute services orchestrated by edge services controller **28**. Processing circuitry **231** may represent any combination of processing cores, ASICs, FPGAs, or other integrated circuits and programmable hardware. In an example, processing circuitry may include a System-on-Chip (SoC) having, e.g., one or more cores, a network interface for high-speed packet processing, one or more acceleration engines for specialized functions (e.g., security/cryptography, machine learning, storage), programmable logic, integrated circuits, and so forth. Such SoCs may be referred to as data processing units (DPUs). DPUs may be examples of processing unit **25**.

In the example NIC **230**, processing unit **25** executes an operating system kernel **237** and a user space **241** for services. Kernel **237** may be a Linux kernel, a Unix or BSD kernel, a real-time OS kernel, or other kernel for managing hardware resources of processing unit **25** and managing user space **241**.

Services **233** may include network, security (e.g., a distributed firewall service), storage, data processing, co-processing, machine learning or other services. Services **233**, edge services platform (ESP) agent **236**, and fabric service **235** include executable instructions. Processing unit **25** may execute instructions of services **233**, ESP agent **236**, and fabric service **235** as processes and/or within virtual execution elements such as containers or virtual machines. As described elsewhere in this disclosure, services **233** may augment the processing power of the host processors (e.g., microprocessor **210**), e.g., by enabling computing device **200** to offload packet processing, security, or other operations that would otherwise be executed by the host processors. Services **233** may also provide security at the edge. Network services of services **233** may include security services (e.g., a distributed firewall), policy enforcement, proxy, load balancing, or other L4-L7 services.

Processing unit **25** executes ESP agent **236** to exchange data with edge services controller **28** (FIG. **1**) for the edge services platform. While shown in the example of FIG. **2** as being in user space **241**, in other examples, ESP agent **236** is a kernel module of kernel **237**. As an example, ESP agent **236** may collect and send telemetry data to edge services controller **28**. The telemetry data may be generated by services **233** and may describe traffic in the network, availability of computing device **200** or network resources, resource availability of resources of processing unit **25** (such as memory or core utilization), or other information. As another example, ESP agent **236** may receive, from edge services controller **28**, service code to execute any of services **233**, service configuration to configure any of services **233**, packets or other data for injection into the network.

Edge services controller **28** manages the operations of processing unit **25** by, e.g., orchestrating and configuring services **233** that are executed by processing unit **25**, deploying services **233**; adding, deleting, and replacing NICs within the edge services platform, monitoring of services **233** and other resources on NIC **230**, and managing connectivity between various services **233** running on NIC **230**. Example resources on NIC **230** include memory **227** and processing circuitry **231**.

Processing circuitry **231** executes fabric service **235** to perform packet switching among NIC **230** and one or more other NICs that are directly connected to NIC **230** ports, i.e., not via an external switch such as TOR switches **16**. Edge services controller **28** may provide topology information to fabric service **235** via ESP agent **236**, the topology information describing a topology of NIC fabric **23**. Edge services controller **28** may provide flow information and/or forwarding information to fabric service **235** via ESP agent **236**. The flow information describes, and is usable for identifying, packet flows. The forwarding information is usable for mapping packets received by NIC **230** to an output port of NIC **230**. In some cases, fabric service **235** may independently compute forwarding information and/or flow information.

Fabric service **235** may determine processing and forwarding of packets received at NIC **230** and bridged by Ethernet bridge **234** to processing unit **25**. A packet received by NIC **230** may have been sent to NIC **230** from a NIC of another computing device or may have originated from user space **245** of computing device **200**. Like other services **233** of NIC **230**, fabric service **235** may process a received packet. Based on information received from edge services controller **28** or generated by fabric service **235**, such as forwarding information and/or flow information, fabric service **235** may map the received packet to an output port that is directly coupled, via a communicate link, to another NIC in the NIC fabric.

FIG. **3** is a conceptual diagram illustrating a data center **300** with servers that each include a network interface card having a separate processing unit, controlled by an edge services platform, according to techniques of this disclosure. Racks of compute nodes **307**A-**307**N (collectively, "racks of compute nodes **307**") may correspond to servers **12** of FIG. **1**, and switches **308**A-**308**N (collectively, "switches **308**") may correspond to the switches of switch fabric **14** of FIG. **1**. An agent **302** or orchestrator **304** represents software executed by the processing unit (illustrated in FIG. **3** as a data processing unit or DPU) and receives configuration information for the processing unit and sends telemetry and other information for the NIC that includes the processing unit to orchestrator **304**. Network services **312**, L4-L7 services **314**, telemetry service **316**, and Linux and software development kit (SDK) services **318** may represent examples of services **233**. Orchestrator **304** may represent an example of edge services controller **28** of FIG. **1**.

Network automation platform **306** connects to and manages network devices and orchestrator **304**, by which network automation platform **306** can utilize the edge services platform. Network automation platform **306** may, for example, deploy network device configurations, manage the network, extract telemetry, and analyze and provide indications of the network status.

FIG. **4** is a block diagram illustrating an example computing device that uses a network interface card having a separate processing unit, to perform services managed by an edge services platform according to techniques described herein. Although virtual machines are shown in this example, other instances of computing device **400** may also or alternatively run containers, native processes, or other endpoints for packet flows. Different types of vSwitches may be used, such as Open vSwitch or a virtual router (e.g., Contrail). Other types of interfaces between endpoints and NIC are also contemplated, such as tap interfaces, veth pair interfaces, etc.

FIG. **5** is a block diagram illustrating an example system **500**, according to techniques of this disclosure. System **500** includes a plurality of servers **512**A-**512**H (collectively, "servers **512**") communicatively coupled via a NIC fabric **523** and a switch fabric **514**. System **500** includes an edge services controller **528**. Each of the plurality of servers **512**A-**512**H may include a corresponding one of NICs **513**A-**513**H (collectively, "NICs **513**"). The NIC fabric **523** includes NICs **513**. The NIC fabric **523** may include a plurality of potential data paths between pairs of NICs **513** that do not traverse switches of switch fabric **514**. Each of these "data paths" is a path through NIC fabric **523** from a source NIC to a destination NIC, and this term is distinct from datapath processing. Edge services controller **528** may be communicatively coupled to each of NICs **513** in NIC fabric **523**. NIC fabric **523** is communicatively coupled to switch fabric **514**. Switch fabric **514** may include one or more switches.

Each of servers **512** may have a configuration similar to the configuration of computing device **200**. Each of NICs **513** may have a configuration similar to the configuration of NIC **230**. Edge services controller **528** may be similar to edge services controller **28**. While eight servers **512** and eight NICs **513** are shown in the example system **500** of FIG. **5**, alternative examples of systems may include a fewer or a greater number of servers **512** and NICs **513**. While each server is shown as including a single NIC, alternative examples of the system may include servers with more than one NIC.

Servers **512** may execute one or more applications. In an example, the one or more applications may be server applications hosted by servers **512** and may represent endpoints, as described with respect to FIG. **1**. In an example, the one or more applications may be NIC applications executed by processing units of NICs **513**. The implementation of data paths between two different NICs at two different servers may involve two stages. The first stage may be an orchestration stage and the second stage may be a forwarding stage. Edge services controller **528** may define or orchestrate one or more data paths between the two different NICs at two different servers during the orchestration stage. Edge services controller **528** may provide data path data associated with the orchestrated data paths to NICs in the data paths. NICs in the orchestrated data paths may forward data packets in accordance with the orchestrated data paths during the forwarding stage. Data path data may be an example of forwarding information described with respect to FIG. **1**.

The implementation of the orchestration stage and the forwarding stage will be described with reference to applications A**1**, A**2** running on server **512**E and applications A**3**, A**4** running on server **512**D. Applications A**1**, A**2**, A**3**, and A**4** may be server applications (e.g., applications executed by the host processors) or may be NIC applications (e.g., applications executed by a processing unit on the NIC). In this example, application A**1** and application A**3** may be services of a service chain, and application A**2** and application A**4** may be services of a service chain.

Application A**1** may be configured to generate application data for transport in data packets, and server **512**E may be configured to send the data packets in accordance with a first protocol for transmission to application A**3**. Application A**1** may be referred to as a first source application A**1** and the application A**3** may be referred to as a first destination application. Application A**2** may be configured to generate application data for transport in data packets, and server **512**E may be configured to send the data packets in accordance with a second protocol for transmission to application A**4**. Application A**2** may be referred to as a second source application A**2** and application A**4** may be referred to as a second destination application. The second protocol may be different from the first protocol.

Examples of the first and second protocols include, but are not limited to, transport layer protocols or tunneling protocols (which may leverage transport layer protocols). The first protocol may for example be a VXLAN protocol. The second protocol may be for example, a Multiprotocol Label Switching/User Datagram Protocol (MPLSoUDP) protocol. While the example is described with reference to VXLAN and MPLSoUDP protocols, other protocols may be used. Server **512**E, which includes source applications A**1** and A**2**, may be referred to as a source server **512**E. NIC **513**E at source server **512**E may be referred to as a source NIC **513**E. Server **512**D includes destination applications A**3** and A**4**, and may be referred to as a destination server **512**D. NIC **513**D at destination server **512**D may be referred to as a destination NIC **513**D.

NICs **513** in NIC fabric **523** and edge services controller **528** may implement NIC-based data packet forwarding. In this environment, processing units **25** in NICs **513** may be shared by services running on associated servers **512** and NIC fabric **523**. If all traffic between a set of two of servers **512** takes the same data path all the time, the traffic between the servers may overload NIC **513** and impact the services running on servers **512**. For example, if traffic from application A**1** to application A**3** and traffic from application A**2** to application A**4** was forwarded on the same data path from source NIC **513**E to destination NIC **513**D, this may result in relatively high utilization of resources of any NICs **513** along that data path and adversely affect performance.

Edge services controller **528** may address this problem by implementing "service aware" or "application-based" routing of the data packets. Edge services controller **528** may orchestrate the application-based data path and one or more of NICs **51** forward data packets in accordance with the orchestrated application-based data path for a pair of applications executing on servers **512** or NICs **513**.

When an application (or service) is deployed at one of servers **512** or at one of NICs **513**, edge services controller **528** may be provided with data regarding the deployed application during the configuration of the deployed application. Examples of such data may include a protocol associated with the deployed application and the other applications that the deployed application may communicate with. Furthermore, when an application is deployed to a host (e.g., one of servers **512**), edge services controller **528** may configure the application's preferred transport in NIC fabric **523**. For example, if a first service (S**1**) and a third service (S**3**) use VXLAN to communicate with each other, and a second service (S**2**) and a fourth service (S**4**) use MPI-.SoUDP for communication, edge services controller **528** may configure NIC fabric **523** to ensure that each application's transport requirements are met. For example, edge services controller **528** may specify, e.g., in a flow table, outer header encapsulation for packets sent between services. The services may be running on top of a host OS or executed by processing units of NICs **513**, or both. In some examples, edge services controller **528** may deploy the applications or devices to servers **512** using the techniques described elsewhere in this disclosure, e.g., based on local Service Level Agreements (SLAs) and external SLAs of NICs **513**.

In an example where NIC **513**E is a source NIC and NIC **513**D is a destination NIC, NIC fabric **523** may include a number of different data paths between source NIC **513**E and destination NIC **513**D. Application of services **233** to packets may utilize compute and bandwidth resources at each of NICs in NIC fabric **523**. In many cases, application of services **233** to packets may utilize a percentage of the total available computing resources at some of NICs **513** and the remaining percentage of computing resources may be available to implement data packet forwarding functions (e.g., fabric service **235**). Each of NICs **513** in NIC fabric **523** may provide resource availability values that indicates available computing resources at that NIC **513** to edge services controller **528**. Example types of resource availability values may include values indicating CPU utilization, network utilization, and so on. Edge services controller **528** may identify, based on the resource availability values, NICs **513** in NIC fabric **523** that are suitable to implement data packet forwarding functions. For example, edge services controller **528** may compare the resource availability values received from each of NICs **513** to a resource availability threshold value, or to compare resource availability of NICs **513** to one another, to identify NICs **513** in NIC fabric **523** that are suitable to implement data packet forwarding functions. Suitable NICs **513** may include NICs **513** that have sufficient computing resources in processing units **25** to apply a fabric service to an expected amount of traffic for the pair of applications communicating, a threshold amount of computing resources, or other criteria. Edge services controller **528** may use the identified NICs to orchestrate data paths between NICs in NIC fabric **523**. When edge services controller **528** orchestrates a data path between a pair of NICs in NIC fabric **523**, edge services controller **528** may provide data path data to NICs logically located along that data path to cause the NICs to forward data packets in accordance with the orchestrated data path.

FIG. **6** is a conceptual diagram illustrating an example close-loop architecture for application-aware services in SmartNICs according to one or more aspects of this disclosure. The close-loop architecture of FIG. **6** includes controller **602** and Performance Analysis and Troubleshooting Engine (PATE analytics unit) **604**. Controller **602** may be an example of or part of edge services controller **28** of FIG. **1** or controller **24** of FIG. **1**. PATE analytics unit **604** may be an example of or part of edge services controller **28**, or may execute on a server or SmartNIC separate from controller **602**.

For example, a Kubernetes cluster (e.g., SmartNIC cluster **606**) may be created with SmartNICs **606**A-**606**N, which may be examples of NICs **13** of FIG. **1**, as regular worker nodes. Controller **602** may be configured to monitor applications that are executing on the SmartNICs (e.g., SmartNIC cluster **606**), which may form a K8s cluster, along with the health of the SmartNIC infrastructure. Beside monitoring, controller **602** may also be configured to provision and manage different application-aware services that are provisioned on the SmartNIC-based worker nodes. For example, two services in controller **602**, namely telemetry collector **610** and action unit **612**, may be responsible for monitoring and management of the applications, respectively.

FIG. **7** is a block diagram illustrating an example telemetry collector architecture **610** in greater detail according to one or more aspects of this disclosure. As seen in FIG. **7**, telemetry collector **610** collects logs and/or metrics from various software and/or hardware components present in the SmartNIC cluster **606**, including SmartNIC **606**A, which is being managed by Controller **602**. Telemetry collector **610** may use a metrics collector **614**, such as a Prometheus metrics collector. Telemetry collector **610** may also use a log collector **618**, such as an Elasticsearch log collector, which may be an open-source log collector. Agents (not shown in FIG. **7**) present in DPUs, service mesh, applications, and operating system(s) (OS) may export metrics and/or logs to metrics collector **614** and log collector **618**, which may store the metrics and/or logs in at least one repository, such as a time series database (TSDB) (e.g., metrics DB **615** and/or logs DB **617**). The collected telemetry information may eventually be consumed by PATE analytics unit **604** for further monitoring and troubleshooting purposes which are explained later in this disclosure.

FIG. **8** is a block diagram illustrating an example action unit **612** architecture in greater detail according to one or more aspects of this disclosure. As seen in FIG. **8**, action unit **612** may be configured to determine a set of actions to be taken based on feedback received or obtained from PATE analytics unit **604**. Examples of actions include, without limitation, applying dynamic security policies for a distributed firewall such as a containerized firewall executing on SmartNIC cluster **606**, actions related to ensuring SLA requirement of the applications by offloading workloads on the SmartNICs (e.g., SmartNICs of SmartNIC cluster **606**), or the like. For different use cases, such as security, or SLA, PATE analytics unit **604** may generate different types of actionable feedback. For each type of feedback, there may be corresponding plugins that are configured to generate a set of actions comprising of one or more actions that are to be performed on managed entities. As shown in FIG. **8**, security action unit **620** may be configured to generate firewall policies for a distributed firewall hosted on the SmartNICs (e.g., SmartNICs of SmartNIC cluster **606**). Similarly, SLA action unit **622** may be configured to dynamically offload workload(s) onto SmartNICs (e.g., SmartNICs of SmartNIC cluster **606**) for performance improvement. Network consistency unit **624** may be configured to provide consistency across the configuration of managed entities, such as SmartNICs, switches, hosts, etc.

FIG. **9** is a block diagram illustrating an example PATE analytics unit **604** architecture in greater detail according to one or more aspects of this disclosure. PATE analytics unit **604** may be configured to collect and analyze application and underlying infrastructure performance telemetry for end-to-end observability and troubleshooting. Depending on the use case, PATE analytics unit **604** may generate actionable feedback that can be consumed by action unit **612** of controller **602** to take corrective steps to remediate the issue.

PATE analytics unit **604** may include cross-layer telemetry ingestion pipeline **630**, anomaly detection service **632**, causality analysis service **634**, and topology analysis service **636**. PATE analytics unit **604** may receive telemetry from multiple layers in the stack, e.g., application, network, compute, firewall, SmartNIC, etc. Cross-layer telemetry ingestion pipeline **630** may be configured to normalize the data model from multiple layers and persist in a TSDB (not shown in FIG. **9**) for further analysis, such as by anomaly detection service **632**, causality analysis service **634**, and topology analysis service **636**, as further described below.

FIG. **10** is a block diagram illustrating an example anomaly detection pipeline according to one or more aspects of this disclosure. Anomaly detection service **632** may include one or more machine learning model(s) **645**, stored in model server **646**. Anomaly detection service **632** may be configured to detect any anomalies in the received timeseries telemetry data from multiple layers in the stack. Anomaly detection service **632** may use, for example, an unsupervised learning-based random cut forest (RCF) approach for detecting any deviation from expected behavior, and/or other unsupervised learning models for detecting anomalies in the received timeseries telemetry data.

Telemetry data from multiple sources across application, compute, and network layers may be ingested by a REST API **640**, e.g., a Kafka service, and then persisted into a TSDB **642**, which may be a Thanos TSDB, for example. Training pipeline **644** may be configured to learn the baseline performance model of different key performance indicators (KPIs) across layers in a network. Model server **646** may be used to host the dynamically learned performance models (e.g., trained machine learning models of machine learning model(s) **645**). During an inference phase, inference pipeline **648** may subscribe to KPI telemetry from API **640** and perform real-time inference for anomaly detection. Whenever an anomaly is detected, depending on the KPIs, an appropriate anomaly detection message indicative of the anomaly may be published on API **640**, which may then be consumed by different subscriber services such as causality analysis service **634** (FIG. **9**).

Referring back to FIG. **9**, causality analysis service **634** may be configured to analyze cross-layer telemetry from the application layer to the network layer (and/or vice versa) to infer where a possible root cause may reside for troubleshooting purposes. For example, where each application includes multiple microservices that are communicating with each other, PATE analytics unit **604** may perform continuous monitoring of each instance of microservices and the interactions of each instance of microservices with other services. Causality analysis service **634** may be configured to determine the possible root cause of application performance degradation. In a microservice-based application, upstream microservice performance may be impacted by the performance of downstream applications. Causality analysis service **634** may analyze, for example, telemetry from each

segment of the call sequence independently and help infer if any downstream microservice is a possible root cause of degraded end-to-end performance of an application.

Topology analysis service **636** may be configured to monitor any topology changes and generate feedback message(s) for consumers at any layer that is being monitored. A non-limiting example of a topology change is a deviation in the normal sequence of order of service calls in a microservice-based application. Topology analysis service **636** may analyze such deviations for each layer to determine topology changes. For example, topology analysis service **636** may determine: i.) a set of new nodes added; ii.) a set of nodes that are removed; iii) a set of new edges; and/or iv) a set of deleted edges. Such an analysis is useful for security use cases such as detection of unwarranted access to services by an intruding service. Topology analysis service **636** may generate an anomaly signal including any results of analysis and provide the anomaly signal as feedback to controller **602** to take remediation action, for example via action unit **612** (FIG. **8**).

A self-correcting framework of this disclosure, such as that of FIG. **6**, may dynamically detect different types of attacks and mitigate these attacks, for example, using a service mesh (e.g., Istio) based microservice application. This disclosure now discusses experiments using a distributed denial-of-service (DDOS) attacker, external attacker, and an internal attacker use cases.

According to the techniques of this disclosure, a system such as that of FIG. **6**, may be configured to execute a machine learning model to determine a traffic prediction based on traffic session metrics data collected over a first period of time. The system may be configured to determine an anomaly in traffic based on a comparison of the traffic prediction to traffic session metrics data collected over a second period of time or at a second time (e.g., current traffic session metrics data). For example, the anomaly may represent a domain name service (DNS) attack, a TCP flood attack, etc. The system may be configured to, based on the determination of the anomaly, generate an indication of the anomaly. The system may be configured to use the indication of the anomaly to determine or generate a firewall policy that is configured to mitigate the anomaly.

FIGS. **11**A and **11**B are conceptual diagrams illustrating example attacker attempts to block the service discovery control plane functionality of service mesh according to one or more aspects of this disclosure. For example, an attacker may attempt to block the service discovery control plane functionality of a service mesh (FIG. **11**A). When successful, such an attack can bring the service mesh down due to failure of service discovery requests from other non-compromised services. Thus, a self-learning firewall policy enforcer may be desirable. An experimental service mesh set up involved a domain name service (DNS)-based service discovery technique on a Kubernetes platform. As shown in FIG. **11**B, a distributed firewall (e.g., DF **650**) may run on every SmartNIC (e.g., POD **1**, POD **2**, and POD **3**) attached to every node of the Kubernetes platform. The distributed firewall may monitor service mesh traffic exiting out and entering each node of the Kubernetes cluster. The distributed firewall may export traffic session metrics to a TSDB (e.g., metrics DB **615** or the like) (not shown in FIGS. **11**A-**11**B for simplicity purposes). PATE analytics unit **604** (also not shown in FIGS. **11**A-**11**B for simplicity purposes) may analyze the exported session metric data from the TSDB to identify a flood of DNS service requests by a compromised pod **654** running on a Kubernetes node. PATE analytics unit **604** may perform such analysis in near real-time and as such, may detect anomalies in near real-time. In some examples, such as when real time learning is desired or needed, the distributed firewall may export traffic session metrics directly to PATE analytics unit **604** in addition to, or in lieu of exporting traffic session metrics to the time series database.

When a service mesh pod (e.g., compromised pod **654**) sends a higher number of service discovery requests within a predetermined period of time than a regular service requests count, PATE analytics unit **604** may identify the sending of the higher number of service discovery requests within the predetermine period of time as an anomaly and notify controller **602** about the anomaly. The regular service requests count may be a number of service requests made by a service in normal cases, such as during a previous time period of a duration equal to the predetermined period of time. The regular service request count may be learned by a machine learning model of machine learning model(s) **645** of model server **646** (FIG. **10**) of PATE analytics unit **604**. For example, when a service runs for some period of time, the service may generate a pattern of numbers of service discovery requests in a timeline. This pattern, which may take the form of a range of service discovery request counts, may be learned by the machine learning model. Similar techniques to those discussed with respect to FIGS. **11**A-**11**B may be similarly applied to identify a TCP flood attack as an anomaly.

In some examples, action unit **612** (FIG. **8**) may dynamically create and/or select a distributed firewall policy to mitigate the anomaly. As shown in FIG. **11**B, any traffic originating from the compromised service of pod **654** may be blocked by the distributed firewall.

FIG. **12** is a graphical diagram illustrating example anomaly mitigation time as the number of attacks are increased according to one or more aspects of this disclosure. As shown, PATE analytics unit **604** may detect and mitigate the anomalies almost instantly under some known pre-conditions, for example, when a machine learning model of machine learning model(s) **645** that PATE analytics unit **604** runs is an already trained model and the mitigation process includes pre-determined firewall rules for the distributed firewall.

FIG. **13** is a table illustrating example anomaly detection for service-discovery-dns-count-per-minute metric according to one or more aspects of this disclosure. The table of FIG. **13** show the performance of the anomaly detection service **632** of PATE analytics unit **604** (both of FIG. **9**) described above. In this use case, PATE analytics unit **604** performs anomaly detection using an unsupervised learning model random cut forest. As seen in FIG. **13**, model accuracy is overall about 98% with a high f-1 score of 97% for anomalies injected due to a DDOS attack as shown in FIG. **11**B.

FIG. **14** is a flow diagram illustrating example anomaly detection according to one or more aspects of this disclosure. The techniques of FIG. **14** are discussed as being performed by different portions of a system with respect to FIG. **6**. Each portion of the system may perform those techniques attributed to the respective portion, or, in some examples, one or more techniques attributed to any one portion of the system may be performed by another portion of the system or combination of portions of the system.

SmartNIC **606**A may send telemetry data to controller **602**, the telemetry data including traffic session metrics data (**660**). For example, SmartNIC **606**A may monitor telemetry associated with SmartNIC **606**A and send telemetry data (e.g., metrics and/or logs) including traffic session metrics,

such as a count of the number of DNS requests made by a virtual network endpoint of a host device of the SmartNIC **606**A, to telemetry collector **610** of controller **602**.

Telemetry collector **610** may monitor service mesh traffic leaving each NIC of a plurality of NICs, each of the NICs comprising NIC processing circuitry (**662**). For example, telemetry collector **610** may monitor service mesh traffic, represented in the telemetry data, leaving SmartNIC **606**A and other SmartNICs of SmartNIC cluster **606**. Telemetry collector **610** may monitor service mesh traffic entering each NIC (**664**). For example, telemetry collector **610** may monitor service mesh traffic, represented in the telemetry data, entering SmartNIC **606**A and other SmartNICs of SmartNIC cluster **606**.

Telemetry collector **610** may determine traffic session metrics data based on the mesh traffic exiting each NIC and the mesh traffic entering each NIC (**666**). For example, telemetry collector **610** may determine a number of DNS requests during various periods of time based on the mesh traffic leaving SmartNIC **606**A and leaving SmartNIC **606**A.

PATE analytics unit **604** may obtain first traffic session metrics data (**668**). For example, PATE analytics unit **604** may receive or retrieve first traffic session metrics data from telemetry collector **610**.

PATE analytics unit **604** may execute a machine learning model to determine a traffic prediction based on first traffic session metrics data (**670**). For example, PATE analytics unit **604** may execute machine learning model(s) **645** (FIG. **10**) to analyze the first traffic session metrics data, for example, to determine a prediction of an expected number of DNS requests. For example, machine learning model(s) **645** may be trained to predict traffic flow, such as a number of DNS requests by a virtual network endpoint of a host device that may be expected over a given predetermined period of time, and PATE analytics unit **604** may compare the number of DNS requests a virtual network endpoint of a host device in the predetermined period of time reflected in the traffic session metrics data to the expected number of DNS requests.

PATE analytics unit **604** may obtain second traffic session metrics data (**672**). For example, PATE analytics unit **604** may receive or retrieve second traffic session metrics data from telemetry collector **610**. The second traffic session metrics data may correlate to traffic after traffic associated with the first traffic session metrics data.

PATE analytics unit **604** may determine an anomaly in traffic based on a comparison of the traffic prediction and the second traffic session metrics data (**673**). For example, PATE analytics unit **604** may determine that a number of DNS requests by a virtual network endpoint of a host device of the traffic session metrics data, within a predetermined period of time, is greater than a number of expected DNS requests for the predetermined period of time based on analysis of the traffic session metrics data.

PATE analytics unit **604** may, based on the determination of the anomaly, generate an indication of the anomaly (**674**). For example, PATE analytics unit **604** may generate an indication of an anomaly to provide to controller **602** and/or SmartNIC **606**A.

Controller **602** may receive or otherwise obtain, from a machine learning model and based on the traffic session metrics data, an indication of an anomaly in traffic (**676**). For example, controller **602** may receive the indication of an anomaly generated by PATE analytics unit **604** in step **674**.

Controller **602** may determine a firewall policy based on the indication of the anomaly (**678**). For example, controller

602 may select a firewall policy from among a plurality of existing firewall policies or generate a new firewall policy to address the anomaly.

Controller **602** may send an indication of the firewall policy to at least one of the one or more NICs (**680**). For example, controller **602** may send the indication of the firewall policy to SmartNIC **606**A.

SmartNIC **606**A may receive, from controller **602**, an indication of a firewall policy based on a determination of an anomaly in traffic based on the traffic session metrics data (**682**). For example, SmartNIC **606**A may receive the indication of the firewall policy from controller **602**. SmartNIC **606**A may implement the firewall policy (**684**). For example, if the indication of the firewall policy identifies an existing firewall policy stored in memory of SmartNIC **606**A, SmartNIC **606**A may load and execute the existing firewall policy. If the indication of the firewall policy includes a new firewall policy, SmartNIC **606**A may store the new firewall policy in memory and/or execute the new firewall policy. In this manner, the techniques of FIG. **14** may stop a current DNS attack and/or prevent a future repetition of the DNS attack in real-time and/or near-real time.

In some examples, PATE analytics unit **604** may send the indication of the anomaly to a controller of a distributed firewall. For example, controller **602** may implement a controller of a distributed firewall. In some examples, the anomaly is indicative of a DNS attack or a TCP flood attack. In some examples, PATE analytics unit **604** may obtain the traffic session metrics data from a time series database (e.g., metrics database **615**). In some examples, the second traffic sessions metrics data includes a number of domain name service requests by a virtual network endpoint of a host device within a period of time, and the traffic prediction includes an expected number of expected domain name service requests during the period of time. In some examples, as part of determining the anomaly, PATE analytics unit **604** may determine the number of domain name service requests by the virtual network endpoint of the host device of SmartNIC **606**A within the period of time is greater than the number of expected domain name service requests. In some examples, the number of expected domain name service requests is based on domain name service requests made during operation over a previous time period (e.g., during regular operation). For example, the number of expected domain name service requests may be learned by a machine learning model such as an unsupervised random cut forest machine learning model. In some examples, the first traffic session metrics data and the second traffic session metrics data are indicative of service mesh traffic. In some examples, the first traffic session metrics data and the second traffic session metrics data are associated with one or more NICs. In some examples, the one or more NICs implement a distributed firewall.

In some examples, controller **602** may generate or select a firewall policy based on the indication of the anomaly. In some examples, the indication of the firewall policy comprises at least one of the firewall policy or an identification of the firewall policy.

In some examples, controller **602** may store the traffic session metrics data in a time series database (e.g., metrics database **615**). In some examples, the traffic sessions metrics data includes a number of domain name service requests by a virtual network endpoint of a host device within a period of time, and the anomaly is indicative of the number of domain name service requests by the virtual network endpoint of the host device within the period of time being greater than a number of expected domain name service requests determined by the machine learning model. In some examples, the number of expected domain name service requests is based on domain name service requests made during a regular operation and is determined by a machine learning model. In some examples, controller **602** may select the firewall policy or generate the firewall policy.

In some examples, the traffic sessions metrics data includes a number of domain name service requests by a virtual network endpoint of a host device within a period of time, and the anomaly is determined by a machine learning model. In some examples, implementing the firewall policy causes SmartNIC **606**A to cease sending domain name services requests from the virtual endpoint of the host device. In some examples, SmartNIC **606**A implements an instance of a distributed firewall.

A mesh egress malware attack is now discussed. In this second use case, an attacker gains access to service mesh applications from outside, such as through a bug in the application or DevOps process, then the attacker can further proceed to attack external web servers, applications, and/or database systems. The attacker may try to steal data and transfer the data to the attacker's external servers. In some cases, attackers may try to download malicious code from their servers into the service mesh. All these cases may result in a change in the regular communication patterns of an application. In this use case, the self-correcting framework, such as that of FIG. **6**, may detect this egress traffic attack and mitigate such an attack, for example, by isolating the compromised application pod using the distributed firewall. PATE analytics unit **604** may use topology analysis service **636** to detect and/or analyze any unwarranted change in application communication patterns. By using telemetry data of the service mesh, topology analysis service **636** may dynamically build a knowledge graph that captures the baseline application communication patterns and continuously monitors the knowledge graph evolution to find any suspicious topology changes.

Experimental results show that the self-correcting close loop framework using topology analysis service **636**, at present, can detect and mitigate the anomalies under 4 minutes. However, the experiment demonstrated that with a real time or a near real time event-based design would further reduce the detection and troubleshooting time for this use case.

A mesh DDOS attack is now discussed. In this third use case, when a service mesh application pod is compromised, an attacker can use the compromised pod to generate malicious traffic to cause some or all the services of the mesh to become unavailable. Though service mesh implementations provide some techniques to prevent these kinds of attacks, these techniques are mostly limited to layer 7 and limited to lower bandwidth traffic.

Similar to the approach for the second use case, PATE analytics unit **604** uses topology analysis service **636** to detect the DDOS attacks. In the experimental set up, self-correcting framework was able to detect the anomalies in the order of minutes.

Additional use cases for a closed-loop framework for implementing application-aware services using SmartNICs are now described. FIG. **15** is a conceptual diagram illustrating example application communication topology before and after an attack according to one or more aspects of this disclosure. For example, communication topology **685** depicts communication pathways between a host, pods, and deployments in a network. Communication topology **687** depicts communication pathways between a host, pods, and deployments after an attack. The attack may cause new service calls between deployments and/or new deployments.

The popularity of SmartNICs may be due to the ability of a SmartNIC to perform packet processing in hardware (e.g., a DPU). This ability allows an application to offload some of the application's packet processing to a DPU, which may improve throughput and packet latency, thus accelerating application workflows. However, the hardware resources in a DPU are limited. For example, the number of flow entries may be limited to 4K (e.g., 4,096) on most DPUs. Other DPU resources, such as an encryption unit, RegEx processing, or the like, have their own limitations. To cut costs, most cloud providers run hundreds of customer applications on the same server. To improve overall system performance, care should be taken to not overwhelm a DPU. Current solutions allocate resources either manually or on a first-come, first-served basis, which may not be optimal.

This disclosure includes techniques to allocate DPU resources, using closed-loop monitoring and machine learning techniques to assign DPU resources as such resources are needed. For example, a system may accelerate applications if the applications are not able to meet their associated SLAs.

FIG. **16** is a conceptual diagram illustrating example auto-SLA enforcement techniques according to one or more aspects of this disclosure. PATE analytics unit **604** may be configured to accelerate an application, such as initiate the offload of portions of the applications or services, from processing circuitry of a server to processing circuitry of a SmartNIC (e.g., a DPU), based on the application not meeting requirements of an associated SLA. For example, a web application **690** may include or utilize encryption, such as IP security (IPSec **694**). In an example, web application **690** may have an SLA requiring 10,000 active connections. PATE analytics unit **604** may continuously monitor the telemetry data of web application **690** and may enable cryptographic offload of IPSec **694** to DPU **692**, for example, if the web application is dropping connections such that the total number of active connections falls below **10,000**, thereby accelerating IPSec **694** to address the failure of web application **690** to meet the requirements of the associated SLA. Similar techniques may be used to dynamically enforce network throughput, packet latency, and/or other SLA requirements.

In some examples, PATE analytics unit **604** may continue to monitor the number of active connections and initiate the moving IPSec **694** back to the processing circuitry of the server if observes a level of improvement in drops of active sessions. For example, PATE analytics unit **604** may initiate offloading IPSec **694** from DPU **692** back to the processing circuitry of the server based on a number of drops or a ratio of drops to active connections or sessions meeting a threshold. In some examples, PATE analytics unit **604** may use one or more machine learning model(s) **645** to determine the threshold.

FIG. **17** is a flow diagram illustrating example offloading techniques according to one or more aspects of this disclosure. PATE analytics unit **604** may obtain telemetry data (**700**). For example, PATE analytics unit **604** may retrieve or receive telemetry data associated with web application **690**.

PATE analytics unit **604** may determine, based on the telemetry data, that an application running on server processing circuitry does not meet at least one service level agreement (SLA) requirement, the server processing circuitry not including processing circuitry resident on a network interface card (NIC) (**702**). For example, PATE analytics unit **604** may determine that web application **690** running on server **696** does not meet an SLA requirement.

PATE analytics unit **604** may, based on the application not meeting the at least one SLA requirement, determine to offload at least one component of the application from the server processing circuitry to the processing circuitry resident on the NIC (**704**). For example, PATE analytics unit **604** may determine to offload IPSec **694** from server **696** processing circuitry onto processing circuitry of DPU **692**.

In some examples, the at least one SLA requirement includes at least one of a number of active connections, a network throughput, or a packet latency. In some examples, the at least one component comprises a cryptographic function. In some example, PATE analytics unit **604** may send a first notification indicative of the determination to offload the at least one component of the application from the server processing circuitry to the processing circuitry resident on the NIC to at least one of the server (e.g., server **696**) or a controller (e.g., controller **602**). In some examples, server **696**, responsive to the first notification, may offload the at least one component of the application from the server processing circuitry to the processing circuitry resident on the NIC.

In some examples, PATE analytics unit **604** may determine, based on the determination to offload the at least one component of the application from the server processing circuitry to the processing circuitry resident on the NIC and based on the analysis of the telemetry data, that the application meets the at least one SLA requirement. PATE analytics unit **604** may determine that a property of the application relating to the at least one SLA requirement meets a threshold. PATE analytics unit **604** may, based on the property of the application meeting the threshold, determine to move the at least one component of the application from the processing circuitry resident on the NIC to the server processing circuitry. In some examples, PATE analytics unit **604** may execute a machine learning model (e.g., machine learning model(s) **645**) to determine the threshold. In some examples, the property of the application comprises a number of drops in a predetermined period of time or a ratio of drops to active connections or sessions during a predetermined period of time.

In some examples, PATE analytics unit **604** may send a second notification indicative of the determination to move the at least one component of the application from the processing circuitry resident on the NIC to the server processing circuitry to at least one of the server or the controller. In some examples, server **696** may, responsive to the second notification, move the at least one component of the application from the processing circuitry resident on the NIC to the server processing circuitry.

FIG. **18** is a conceptual diagram illustrating example self-learning flow priority techniques according to one or more aspects of this disclosure. One of the popular services deployed by many users in a SmartNIC environment is a distributed firewall. Policing East-West traffic in a datacenter, where traffic rate may be on the order of 100×Tbps, may be difficult for network administrators. Running a firewall on a SmartNIC may solve this problem by policing the traffic at a host instead of in the network. Typically, a firewall works by applying all configured policies for each incoming and outgoing packet to determine if the packet should to be permitted or denied. Because applying every policy for every packet may be exceedingly time consuming, to speed up processing, a firewall may create a flow table entry for each new flow and use cached information in the flow table to process future packets of that flow. For example, the firewall may apply multiple policy lookups to every first packet of a flow. The firewall may skip the multiple policy lookups for the subsequent packets of the flow, but such subsequent packets may still go through the flow processing stage (e.g., looking up the subsequent packets in the flow table). This whole sequence of lookups may also be time consuming and may take up significant amount of CPU resources, which may limit the overall throughput of a firewall.

As such, to improve firewall throughput, a distributed firewall may analyze flows where flow processing is performed based on a flow's criticality or importance. For example, one or more machine learning models **645** of PATE analytics unit **604** may learn each application's flows and rank each application in the order of the importance of the application, such as in terms of weights. For example, PATE analytics unit **604** may predict the weight of flows based on the criteria set forth below. As such, the techniques described herein may improve firewall throughput. For example, rather than handle flow processing for each subsequent packet of a flow, a firewall may perform flow processing based on flow criticality or importance. Using dynamic telemetry data, one or more machine learning models **645** may learn each application's flows and rank the flows in an order based on importance of the respective flow. Example criteria which may be used to determine a flow ranking based on importance include, but are not limited to, flow hit rate, hit rate of related flows, flow close missed rate, flow metric criticality, or the like.

Flow Hit Rate (FHR) may be a number of successful firewall flow evaluations out of a total number of evaluations. For example, FHR may be calculated as:

FHR=Number of Successful Flow Evaluations/Total Number of Evaluations

Related Flow Hit Rate (RFHR) may be an average of hit rate of flows related to the flow. For example, if two flows contain commonality in any of the below attributes, those two flows may be considered as related flows. Such attributes may include, source address, destination address, source port, destination port, protocol, or the like. For example, RFHR may be calculated as:

RFHR=(Total Hit Rate of all related flows)/(Total Number of Evaluations of all related flows).

In some example, the flow itself may be excluded when calculating RFHR.

Flow Close Missed Rate (FCMR) may be a ratio of number of close miss evaluation of flows over a number of total flow evaluations. A close evaluation miss may be defined as a flow evaluation failure due to a mismatch of a user configured threshold number of attributes. For example, if flow has 5 attributes for evaluation and user configured a close miss threshold as 2. Then, if flow evaluation failed due to mismatch of 2 (or fewer) attributes, then flow evaluation will be considered as close miss evaluation. For example, FCMR may be calculated as

FCMR=(Number of Close Missed Evaluations)/(Total number of Evaluations).

Flow Criticality may be indicated by a flag. For example, a flag may be attached to a flow when any of the attributes involved in the flow is deemed to be a part of a critical event and flagged by user by labelling flow as critical at run time. For example, when user observes a suspicious security threat log event, the user may label all related flows as critical flows. When a flow is labelled as critical, the weight

of the flow may be automatically set to a maximum. In such an example, the flow evaluator would prioritize the flow for evaluation.

Using above referenced analytics, PATE analytics unit **206** may determine or predict a weight for each flow. Depending on the weight of the flow, a flow processor of the distributed firewall may evaluate the flows. These analytics are performed periodically over the evaluation history and flow weight is predicted or updated. For example, if Flow Hit Rate is R**1**, the Related Flow Hit Rate is R**2**, the Flow Close Missed Rate is R**3**. PATE analytics unit **604** may predict or determine a flow weight using a linear regression formula and above calculated individual rates:

$$W1=a+b(R1)$$

$$W2=a+b(R2)$$

$$W3=a+b(R3)$$

where $a=(\Sigma Wi)(\Sigma Ri*2)-(\Sigma Ri)(\Sigma WiRi)/n(\Sigma Ri*2)-(\Sigma Ri)2$

$$b=n(\Sigma WiRi)-(\Sigma Ri)(\Sigma Wi)/n(\Sigma Ri*2)-(\Sigma Ri*)2$$

PATE analytics unit **604** may then determine a mean of the predicted weights (W**1**, W**2**, and W**3**) as weight of the flow:

$$WR=(\Sigma_{i=1}^{n} Wi)/n$$

PATE analytics unit **604** may send flow order rank to the distributed firewall. The flow processor of the distributed firewall may evaluate the flows based on these dynamically predicted weights.

As shown in FIG. **18**, the example closed-loop system may determine a ranking and provide the ranking back to a firewall module (e.g., DPUs **670**A-**670**B). The distributed firewall may in turn process each flow proportional to the flow ranking. For example, the firewall may process a higher ranked flow more often than a lower ranked flow. This may reduce the number of flows the firewall needs to process for each packet, which may increase the firewall throughput. Based on the above calculated analytical metrics, a weight factor can be calculated for every flow to indicate the priority and importance of the flow. The higher weight factor may indicate a higher priority, and that the higher priority flow should be processed first and/or more frequently than other flows having lower weight. This technique of dynamic priority prediction for flows also enables the distributed firewall to process the flows in any order rather than only on descending order. That means, the flow processor can pick flows in the inverse order of their weights. This may cause most failed flows to be evaluated on priority.

FIG. **19** is a flow diagram illustrating example flow ranking techniques according to one or more aspects of this disclosure. PATE analytics unit **604** may obtain telemetry data, the telemetry data including flow processing data associated with a plurality of flows (**720**). For example, PATE analytics unit **604** may retrieve or receive the telemetry data from controller **602**.

PATE analytics unit **604** may rank the plurality of flows indicated by the telemetry data according to importance (**722**). For example, PATE analytics unit **604** may assign a respective ranking to each flow of the plurality of flows. The respective ranking may represent a determined level of relative importance of the respective flow.

PATE analytics unit **604** may send information indicative of a respective rank of at least one of the plurality of flows to at least one of a controller or a network interface card

(NIC), the NIC comprising NIC processing circuitry (**724**). For example, PATE analytics unit **604** may send the respective rank of one or more of the plurality of flows to controller **602** or SmartNIC **606**A.

In some examples, as part of ranking the plurality of flows indicated by the telemetry data according to importance, PATE analytics unit **604** may, for each respective flow of the plurality of flows, determine importance criteria, the importance criteria including at least one of: a flow hit rate, wherein the flow hit rate includes a number of successful firewall flow evaluations for the respective flow out of a total number of evaluations for the respective flow during a time period; a related flow hit rate, wherein the related flow hit rate includes an indication of a number of successful firewall flow evaluations for one or more related flows to the respective flow out of a total number of evaluations for the one or more related flows during the time period; a flow close missed rate, wherein the flow close missed rate includes an indication of the number of failed firewall flow evaluations for the respective flow meeting an attribute threshold out of the total number of evaluations for the respective flow during the time period; or a flow criticality.

In some examples, as part of ranking the plurality of flows indicated by the telemetry data based on importance, PATE analytics unit **604** may determine a respective importance of each respective flow based on the importance criteria associated with the respective flow. In some examples, each of the one or more related flows includes a commonality in at least one attribute with the respective flow. In some examples, the at least one attribute includes at least one of a source address, a destination address, a source port number, a destination port number, or a protocol.

In some examples, as part of determining the flow close missed rate, PATE analytics unit **604** may determine a first number of attributes of the respective flow that failed during a first firewall flow evaluation of the respective flow; determine that the first number of attributes meets the attribute threshold; and based on the first number of attributes meeting the attribute threshold, classify the first firewall flow evaluation of the respective flow as a close miss; determine a second number of attributes of the respective flow that failed during a second firewall flow evaluation of the respective flow; determine that the second number of attributes does not meet the attribute threshold; and based on the second number of attributes not meeting the attribute threshold, classify the second firewall flow evaluation of the respective flow as not being a close miss. In some examples, the attribute threshold is user definable.

In some examples, flow criticality is indicatable by a user selectable flag, the user selectable flag indicating either a highest importance or not a highest importance. In some examples, an indication of a highest importance causes the network system (e.g., PATE analytics unit **604**) to rank the respective flow as being of a highest importance and wherein an indication of not a highest importance causes the network system to utilize other importance criteria to determine the importance of the respective flow. In some examples, PATE analytics unit **604** may execute a machine learning model to rank the plurality of flows indicated by the telemetry data based on importance. In some examples, SmartNIC **606**A may process one or more of the plurality of flows in accordance with the ranking.

FIG. **20** is a flow diagram illustrating example packet processing techniques of a firewall service according to one or more aspects of this disclosure. FIG. **19** shows the packet processing pipeline of a firewall service. When a packet reaches a firewall (e.g., a distributed firewall such as may be implemented on DPUs **710**A-**710**B), the firewall may construct a flow ID (e.g., SIP, DIP, SPORT, DPORT, PROTO) from the packet header of the packet (**730**). The firewall may search for this flow ID in a flow table to determine if this is an existing flow or a new flow (**732**). If the flow is an existing flow (the "Yes" path from box **732**), the packet may stay in the data path, and the firewall may perform the action present in the flow table (**734**). For example, the firewall may apply a policy based on the flow table. If the flow is a new flow (the "No" path from box **732**), the firewall may send the packet to a control-plane, which may analyze the configured policies (which may number in the thousands) to identify the action which the firewall should take for all future packets in this flow. This control plane lookup may be time consuming, and may block or delay the forwarding of all packets in that flow until lookup is complete. For example, if the flow is a new flow (the "No" path from box **732**), the firewall may determine whether the new flow is currently being processed by a control-plane of the firewall (**736**). If the new flow is not currently being processed by the control plane (the "No" path from box **736**), the control plane may look up the configured policies, analyze the configured policies, determine the action which the firewall should take for all future packets in this flow, and create an entry for the new flow in the flow table indicative of which action should be taken for packets of the new flow (**738**). If the new flow is currently being processed by the control plane (the "Yes" path from box **736**), the control plane may determine whether a buffer is full (**740**). This buffer may be used to store packets of new flows waiting to be processed so as to not drop such packets. If the buffer is not full (the "No" path from box **740**), the control plane may store the packet in the buffer until an entry for the flow is completed in the flow table (**742**). However, if the buffer is full (the "Yes" path from box **740**), the packet is dropped (**744**). In a traditional firewall, packet buffers are limited as the system must support thousands of active flows, which may result in a large number (in some cases, most) of the packets being dropped while a flow entry in the flow table is created.

In typical enterprise datacenters, most applications follow predictable patterns. For example, administrators usually schedule backups in the middle of the night when most resources are free. Using continuous monitoring and machine learning by PATE analytics unit **604**, PATE analytics unit **604** may learn the behavior (e.g., patterns) of the applications. As such, a firewall may create flow entries related to backup services in advance, which may increase a speed of backups.

FIG. **21** is a flow diagram illustrating example policy table population techniques according to one or more aspects of this disclosure. PATE analytics unit **604** may obtain telemetry data, the telemetry data including indications of creations of instances of a flow (**750**). For example, PATE analytics unit **604** may retrieve or receive the telemetry data from controller **602**.

PATE analytics unit **604** may, based on the indications of the creations of the instances of the flow, determine a pattern of creation of the instances of the flow (**752**). For example, instances of the flow have a pattern to their creation, such as being regularly created at a certain time and/or day of the week.

PATE analytics unit **604** may, based on the pattern of creation of the instances of the flow, generate an action entry in a policy table for a particular instance of the flow prior to receiving a first packet of the particular instance of the flow (**754**). For example, PATE analytics unit **604** may predict that a particular instance of the flow will be created based on the pattern of creation of the plurality of instances of the flow and generate the action entry based on the prediction.

In some examples, the creation of the instances of the flow occurs prior to the creation of the particular instance of the flow. In some examples, as part of determining the pattern of creation of the instances of the flow, PATE analytics unit **604** may execute a machine learning model (e.g., machine learning model(s) **645**). In some examples, as part of the generating the action entry, PATE analytics unit **604** may execute a machine learning model (e.g., machine learning model(s) **645**). In some examples, the machine learning model is an unsupervised machine learning model. In some examples, the machine learning model is trained using respective indications of a plurality of creations of instances of a plurality of flows.

In some examples, SmartNIC **606**A may receive the first packet of the particular instance of the flow. SmartNIC **606**A may determine an action based on the action entry in the policy table and execute the action on the first packet of the particular instance of the flow. In some examples, the action entry relates to a backup service.

FIG. **22** is a block diagram illustrating an example firewall policy optimizer according to one or more aspects of this disclosure. Firewall software is typically divided into three primary components, a management plane **760**, a control plane **762** (mentioned above), and a data plane **764**. In some examples, management plane **760** may be located in a distributed firewall controller, such as in controller **602**. In a distributed firewall, whenever a new instance of the firewall is created, management plane **760** may send all the user configured policies to this new instance of the firewall. In some complex deployments, these policies can be in the range of a few thousand. Control plane **762** on a local host **766** may apply all these policies to every first packet of a flow to create forwarding tables, as mentioned above.

For every first packet of a new flow, all the policies are applied to the first packet and the result of the application of the polices is used to update the flow table. This operation may be expensive and consume many CPU cycles, which limits the scaling of the firewall as the firewall may usually process thousands of flows every second. Even though management plane **760** typically sends all configured policies to control plane **762**, control plane **762** may only require the policies used by applications (current or future) running on that particular host, e.g., host **766**. As such, the techniques of this disclosure include using dynamic telemetry data, a closed-loop PATE machine learning unit (e.g., one or more machine learning model(s) **645**) of PATE analytics unit **604** may learn firewall policies used by each application, and which applications are running or expected to be running on a particular host. Such information may be obtained by management plane **760**. For example, PATE analytics unit **604** may send such information to management plane **760**. Management plane **760** may use such information to prune the policy set that management plane **760** may send to a given host based on the host's determined and/or predicted current and future needs.

For example, if PATE analytics unit **604** determines that a particular policy is predicted to be used for a given host, management plane **760** may include that policy in the firewall policy set sent to the control plane of that host. If PATE analytics unit **604** determines that a particular policy is not predicted to be used for a given host, management plane **760** may remove that policy from the firewall policy set sent to the control plane of that host. In this manner, only the policies predicted to be used by the host may be sent to the host. As the host may only receive a subset of the

policies, the control plane of the host may only apply a reduced set of policies to the first packet of any flow, thereby reducing the CPU cycles required for the firewall instance.

For example, when a packet is received by control plane **762**, control plane **762** may determine if the packet is a first packet of a flow or a packet of an existing flow. If the packet is a first packet of a flow, control plane **762** may perform a flow table lookup and apply all policies applicable to the flow. If the packet is a packet of an existing flow or has already had all the policies applied, control plane **762** may perform a flow table lookup to determine how to handle the packet and then provide the packet to the forwarding unit.

FIG. **23** is a flow diagram illustrating example techniques for reducing a number of firewall polices distributed to nodes of a distributed firewall according to one or more aspects of this disclosure. PATE analytics unit **604** may obtain telemetry data, the telemetry data being associated with a plurality of applications running on a plurality of hosts (**780**). For example, PATE analytics unit **604** may retrieve or receive the telemetry data from controller **602**. As used herein, a plurality of applications running on a plurality of hosts means that an application of the plurality of applications may run on one or more of the plurality of hosts and does not necessarily require that each application runs on each host or that all applications run on every host.

PATE analytics unit **604** may, based on the telemetry data, determine a subset of applications of the plurality of applications that run on a first host of the plurality of hosts (**782**). For example, PATE analytics unit **604** may determine that only a portion of the plurality of applications actually normally run on a particular host (e.g., host **766** of FIG. **22**).

PATE analytics unit **604** may determine a subset of firewall policies of a plurality of firewall polices, each of the subset of firewall policies applying to at least one respective application of the subset of applications (**784**). For example, PATE analytics unit **604** may determine which firewall policies actually apply to each of the applications in the subset of applications and determine the subset of firewall policies such that each firewall policy in the subset of firewall policies apply to at least one of the applications in the subset of applications.

PATE analytics unit **604** may generate an indication of the subset of firewall policies (**786**). PATE analytics unit **604** may send the indication to a management plane of a distributed firewall (**788**). For example, PATE analytics unit **604** may send an indication identifying the subset of firewall policies to a firewall controller, such as controller **602**.

In some examples, PATE analytics unit **604** may execute a machine learning model to determine at least one of which applications run on the host or which firewall policies apply to the determined applications. In some examples, the machine learning model is an unsupervised machine learning model.

In some examples, the host includes a network interface card (NIC), the NIC comprising NIC processing circuitry. In some examples, an instance of a control plane and a data plane of the distributed firewall runs on the host.

In some examples, a management plane may receive the indication. In some examples, the management plane may prune a firewall policy set corresponding to the plurality of firewall policies based on the indication, to generate a pruned firewall policy set, the pruned firewall policy set corresponding to the subset of firewall policies. In some examples, the management plane may send, to a control plane of an instance of the distributed firewall executing on the host, the pruned firewall policy set.

In some examples, SmartNIC **606**A may apply only the pruned firewall policy set to a first packet of a new flow. In some examples, as part of applying only the pruned firewall policy set to the first packet of the new flow, SmartNIC **606**A may apply each policy of the pruned firewall policy set to the first packet of the new flow and refrain from applying any policy of the firewall policy set that is not a part of the pruned firewall policy set.

As discussed herein, implementing different network service on SmartNICs using a closed-loop framework may be effective in identifying and responding to network attacks. PATE analytics unit **604** may detect anomalies and topology changes which may be used by controller action unit **612** to dynamically control operations of a distributed firewall which may be implemented on SmartNICs to remediate the security threats. Moreover, additional use cases are set forth where this framework may be used for SLA improvement and security firewall scalability and optimization.

FIG. **24** is a conceptual diagram illustrating example egress traffic-based attacks according to one or more aspects of this disclosure. When a microservice-based application is deployed in a Kubernetes or service mesh-based environment, network security typically emphasizes traffic coming into the cluster ("ingress traffic"). Sometimes, when a zero-trust policy is preferred, it may be desirable for network security to monitor and secure cluster internal traffic. But, when an application is compromised due to, for example, a bug in the application code, a malicious supply chain or DevOps pipelines, an attacker may use the compromised application service either to attack any external servers or to download malware from the attacker's server(s). The monitoring and securing of outgoing traffic are therefore desirable to prevent egress traffic-based attacks.

For example, a bug in security code may exist which may be executing within cluster network **792** of a data center. An attacker may exploit that bug to gain access to and compromise reviews service **790** within cluster network **792**. The attacker may then, from reviews service **790** via egress traffic, log into the attacker's home server **794** to download malware to cluster network **792**, for example.

As a basic step to secure egress network traffic, Kubernetes provides a cluster network policy to help the cluster administrator to configure static network policies (e.g., policies that remain in place until changed or deleted) to control access to external servers by the application service. For example, a plugin for Kubernetes may provide support for cluster network policies as well as provide cluster networking. However, such a network policy approach has some limitations. For example, such an approach may be IP address-based and may not support domain names in the cluster network policies, may not handle high bandwidth traffic, may consume a large amount of compute resources of the cluster node for filtering traffic, and/or may negatively affect traffic bandwidth when application services or network polices are scaled.

When an application is deployed in a service mesh, egress traffic may be monitored and controlled using reverse proxies (e.g., an "egress gateway"). The egress gateway may run at an edge of a cluster. The application services which may want to communicate to external servers may be configured to only reach the external servers through an egress gateway. However, such an egress gateway approach may have limitations as well. For example, such an egress gateway approach may be bypassed as application services may bypass the egress gateway by making a direct external network connection, may add an additional network hop in the external service communication, may centralize external traffic and cause a single point of failure, may work only with TLS and HTTP traffic, may cause issues with management of egress gateway instances for scalability and/or availability, may consume compute resources of cluster nodes, and/or may not handle high bandwidth traffic well.

As such, according to the techniques of this disclosure, a self-learning egress traffic controller is disclosed. For example, self-learning knowledge graph-based distributed firewall techniques may detect malicious egress connections and mitigate the attacks caused by malicious egress connections. These techniques may use distributed firewalls to monitor external traffic and mitigate any possible egress traffic-based attacks at a cluster node level. The distributed firewall may run on one or more SmartNICs attached to, in some examples, every node of a cluster. For example, every node in the cluster may be attached to a SmartNIC and the traffic of every node in the cluster may pass through the SmartNIC.

The SmartNICs attached to each cluster node may be managed by a component, such as a SmartNIC controller. The SmartNIC controller may orchestrate the distributed firewalls running on these SmartNICs. For example, the SmartNIC controller may learn the application topology using past network communication metrics data of the application running on the cluster nodes. The learned application topology may help the SmartNIC controller identify malicious or compromised services which may make egress connections to initiate egress traffic-based attacks, like malware attacks.

FIG. **25** is a conceptual diagram illustrating an example self-learning egress traffic controller according to one or more aspects of this disclosure. As shown in FIG. **25**, these techniques utilize telemetry data exporters, such as node network metrics exporter (NNME) **802** on cluster nodes, such as cluster node-1 **804**, and their respective SmartNICs, such as SmartNIC-1 **806**. When a service makes a network connection, a cluster network provider, such as cluster network provider **808**, may perform network address translation (NAT) and route the connections further depending on the destination address. Typically, in Kubernetes environment, a cluster network provider may perform source NAT (SNAT) when the destination address does not belong to the cluster network address range. In this case, a distributed firewall running on the SmartNICs may not be able to obtain an actual source IP address of the service which initiated the connection. To obtain the actual source address, the cluster network provider may export the network connection metrics containing connection attributes like source IP address and port number, destination address and port, or the like. However, when SNAT is disabled at the cluster network provider, the exporting of metrics may be disabled at the cluster network provider.

As such, the techniques of this disclosure may include the following metric exporters. One solution involves one or more cluster node network metric exporters (e.g., node network metrics exporter (NNME) **802**) and one or more firewall metrics exporters (e.g., firewall metrics exporter (FME) **810**) to provide the input data for training a machine learning model (e.g., machine learning model(s) **645**).

In some examples, a cluster node network metric exporter (e.g., node network metrics exporter **802**) may run on every cluster node to export the connection metrics provided by a cluster network provider, such as cluster network provider **808**. Node network metrics exporter **802** mainly exports the metrics with connection details as labels for every connection originated by workloads (which may be containers or pods) running on the cluster node. Example labels include source and destination IP address, source and destination port number, source workload name (which may include a pod or container name), connection protocol and direction, cluster node name and identification (ID), and/or the like.

A firewall metrics exporter (e.g., firewall metrics exporter **810**) may run on a SmartNIC (e.g., SmartNIC (SN) **806**) of every cluster node and export connection metrics provided by the distributed firewall (which may include firewall **812**). Firewall metrics exporter **810** mainly exports metrics with connection attributes as metric labels. Example labels include source and destination IP address, source and destination port number, direction, and/or the like.

A metric collector, such as telemetry metric collector **814**, may collect the metrics exported by node network metrics exporter **802** and firewall metrics exporter **810**. Telemetry metric collector **814** may be run within SmartNIC controller **816** or somewhere inside or outside of data center network **800**. SmartNIC controller **816** may be an example of controller **602** of FIG. **6**. In some examples, telemetry metric collector **814** may include an event queue, for example, when real time metric data is desirable. Telemetry metric collector **814** may feed the collected metric data to a topology analytical service, such as topology analysis and learning engine (TALE) unit **820**. TALE unit **820** may be an example of topology analysis service **605** of PATE analytics unit **604** of FIG. **6**.

TALE unit **820** may analyze the network connection metric data and build a knowledge graph representing the communication topology of all services of the application. TALE unit **820** may include a machine learning model (similar to machine learning model(s) **645** of FIG. **10**) which may be trained using historical communication data of the application. TALE unit **820** may analyze historical metric data obtained by TALE unit **820** and build the knowledge graph based on the historical metric data. In some examples, TALE unit **820** may be configured to use the dynamic communication data of the application to build the knowledge graph.

In some examples, when a network connection is made by an application service and a metric is exported associated with the network connection, TALE unit **820** may analyze the metric label data and start building a knowledge graph. TALE unit **820** may map source workload name to a knowledge graph node and may map any network connection from that workload to a graph edge. For example, {Source Workload Name}->Knowledge Graph Node, and {Source IP Address, Destination IP Address}->Knowledge Graph Edge services.

FIG. **26** is a conceptual diagram illustrating example an application knowledge graph before egress attacks according to one or more aspects of this disclosure. FIG. **26** depicts a knowledge graph **830** built by TALE unit **820** using historical data of a simple e-commerce application. Knowledge graph **830** shows that only billing service **832** makes (e.g., is permitted to make) egress connections, such as the egress connection to payment gateway **834**. TALE unit **820** may continuously analyze the live metric data and update knowledge graph **830** of the application. But when an application service gets compromised, e.g., due to a bug in the application code, errors in a supply chain, or compromised DevOps pipelines, the application may attempt to dial the application's home server or the attacker's server to download malicious code or malware. Further, the application may try to exfiltrate other external services by initiating egress connections towards the other external services.

When a compromised service makes malicious egress connections, TALE unit **820** may receive metric data related

to these new connections. Using the received metric data, TALE unit **820** may update the knowledge graph **830** with new graph nodes and edges. When knowledge graph **830** is updated, TALE unit **820** may analyze the updated knowledge graph to determine any changes in the topology. When there are changes to knowledge graph **830**, TALE unit **820** may generate a network anomaly event with details about any new egress connection(s).

FIG. **27** is a conceptual diagram illustrating example updated knowledge graph according to one or more aspects of this disclosure. For example, TALE unit **820** may update knowledge graph **830** to generate updated knowledge graph **840**. As shown in FIG. **27**, when reviews service **850** of the e-commerce application becomes compromised, an attacker may use reviews service **850** to initiate an egress connection towards the attacker's server **852** and external payment gateway service **854**. TALE unit **820** identifies these new egress connections as anomalous connections because TALE unit **820** has learned that only billing service **856** makes egress connections.

When TALE unit **820** generates network anomaly event(s) for new egress connection(s), an action service (e.g., action unit **818**) running within SmartNIC controller **816** receives these events. The action service may process the anomaly events and configure a firewall policy to mitigate the attack, for example, by stopping all traffic of compromised service (e.g., reviews service **850**).

FIG. **28** is a sequence diagram illustrating example techniques for configuring a firewall policy to mitigate an egress attack to one or more aspects of this disclosure. For example, a compromised service (e.g., reviews service **850** may make egress connection **860** to cluster network provider **808**. Cluster network provider **808** may provide connection data **862** to node network metrics exporter **802** and route the connection **864** to the distributed firewall, which may include firewall **812**. Firewall **812** may provide connection data **866** to firewall metrics exporter **810**. Telemetry metrics collector **814** may collect node network metrics **868** from node network metrics exporter **802** and collect firewall connection metrics **870** from firewall metrics exporter **810**. While shown as being initiated from telemetry metrics collector **814**, in some examples, telemetry metrics collector **814** may passively receive metrics from node network metrics exporter **802** and/or firewall metrics exporter **810**. Telemetry metrics collector **814** may feed metrics data **872** to TALE unit **820**. TALE unit **820** may build a knowledge graph **874**, such as updated knowledge graph **840**. TALE unit **820** may analyze the knowledge graph **876**, and notify action service (e.g., action unit **818** of FIG. **25**) of an anomaly event **878**. The action service may create (e.g., generate) a new firewall policy **880** or modify an existing firewall policy. The action service may apply the new firewall policy or the modified firewall policy **882** to the distributed firewall (e.g., firewall **812**) to mitigate the egress attack.

FIG. **29** is a flow diagram illustrating example techniques for configuring a firewall policy to mitigate an egress attack to one or more aspects of this disclosure. For example, a compromised service (e.g., reviews service **850** of FIG. **27**) may make an egress connection to attacker's server **852** (**900**). Telemetry metrics collector **814** may collect metrics from node network metrics exporter **802** and/or firewall metrics exporter **810**. Telemetry metrics collector **814** may export network metrics (**902**) to TALE unit **820**. TALE unit **820** may analyze metrics data (**904**). TALE unit **820** may validate egress connection (**906**). For example, TALE unit **820** may determine whether the egress connection is permitted based on existing knowledge graphs. TALE unit **820** may determine whether the connection is an anomaly connection (**908**). For example, TALE unit **820** may determine whether the connection is permitted based on existing knowledge graphs. If TALE unit **820** determines the connection is not an anomaly connection (the "No" path from box **908**), TALE unit **820** may ignore the connection (**910**). If TALE unit **820** determines the connection is an anomaly connection (the "YES" path from box **908**), TALE unit **820** may report the anomaly event (**912**) to action unit **818**. Action unit **818** may process the anomaly and create a firewall policy (**914**). Action unit **818** may apply the firewall policy (**916**) to the distributed firewall which may employ the firewall policy.

FIG. **30** is a flow diagram illustrating example techniques for responding to malicious egress connections according to one or more aspects of this disclosure. The techniques of FIG. **30** are discussed as being performed by different portions of a system with respect to FIG. **6**. Each portion of the system may perform those techniques attributed to the respective portion, or, in some examples, one or more techniques attributed to any one portion of the system may be performed by other portion of the system or combination of portions of the system.

SmartNIC **606**A may configure an egress connection from an application service of an application (**920**). For example, SmartNIC **606**A may make a connection from reviews service **850** to payment gateway **854** (FIG. **27**).

SmartNIC **606**A may send, to a computing device, connection data related to the egress connection (**924**). For example, SmartNIC **606**A may generate, log, and send the connection data to controller **602**, which may be a SmartNIC controller, such as SmartNIC controller **816** of FIG. **25**.

Controller **602** may receive connection data related to an egress connection of an application service of an application (**926**). For example, controller **602** may receive the connection data from SmartNIC **606**A. Controller **602** may send, to a computing device, the connection data (**928**). For example, controller **602** may send the connection data to PATE analytics unit **604**. In some examples, controller **602** may process the connection data prior to sending the connection date to PATE analytics unit **604**.

PATE analytics unit **604** may obtain connection data related to an egress connection of an application service of an application (**930**). For example, PATE analytics unit **604** may retrieve or receive the connection data from controller **602**.

PATE analytics unit **604** may analyze the connection data to determine that the egress connection is an anomalous connection (**932**). For example, PATE analytics unit **604** may determine that the egress connection is not an expected egress connection and is therefore anomalous.

PATE analytics unit **604** may generate a notification indicative of the egress connection being an anomalous connection (**934**). PATE analytics unit **604** may send the notification to a computing device (**936**). For example, PATE analytics unit **604** may send the notification to controller **602**.

Controller **602** may receive, from the computing device and in response to sending the connection data, a notification indicative of the egress connection being an anomalous connection (**938**). For example, controller **602** may receive the notification indicative of the egress connection being an anomalous connection from PATE analytics unit **604**.

Controller **602** may generate, based on the notification indicative of the egress connection being anomalous, a notification to apply a firewall policy (**940**). For example, controller **602** may determine a firewall policy that should be applied by SmartNIC **606**A to address the anomalous connection and may generate notification thereof.

Controller **602** may send the notification to apply the firewall policy to at least one network interface card (**942**). For example, controller **602** may send the notification to apply the firewall policy to SmartNIC **606**A.

SmartNIC **606**A may receive, from the computing device and in response to sending the connection data, a notification to apply a firewall policy (**944**). For example, SmartNIC **606**A may receive from controller **602**, the notification to apply the firewall policy. SmartNIC **606**A may apply the firewall policy (**946**). For example, SmartNIC **606**A may extract a firewall policy from the notification and execute the firewall policy or may determine an identification of a firewall policy based on the notification, load the firewall policy from memory, and execute the firewall policy.

In some examples, PATE analytics unit **604** may analyze the connection data via a machine learning model (e.g., machine learning model(s) **645**). In some examples, the machine learning model is trained using previous connection data of the application.

In some examples, PATE analytics unit **604** may generate a previous knowledge graph (e.g., knowledge graph **830** of FIG. **26**) based on previous connection data of the application. In some examples, the previous knowledge graph is indicative of each application service of the application that has previously made egress connections. In some examples, as part of analyzing the connection data, PATE analytics unit **604** may generate a first knowledge graph based on the connection data, the first knowledge graph (e.g., knowledge graph **840** of FIG. **27**) being indicative of the application service making the egress connection. PATE analytics unit **604** may compare the first knowledge graph to the previous knowledge graph.

In some examples, the connection data includes node network metrics and firewall metrics. In some examples, at least a portion of the node network metrics are associated with a cluster node, and wherein the node network metrics comprise at least one of a source IP address, a destination IP address, a source port number, a destination port number, a source workload name, a connection protocol and direction of the egress connection, or a cluster node identifier. In some examples, at least a portion of the firewall metrics are associated with an instance of a distributed firewall running on a NIC, and wherein the firewall metrics comprise at least one of a source IP address, a destination IP address, a source port number, a destination port number, or a direction of the egress connection.

In some examples, the notification indicative of the egress connection being an anomalous connection comprises information associated with the egress connection. In some examples, the firewall policy is a new firewall policy. In some examples, the notification to apply the firewall policy includes the new firewall policy.

In some examples, SmartNIC **606**A may, as part of applying the firewall policy, at least one of drop the egress connection or block further egress connections from the application service. In some examples, as part of generating the notification to apply the firewall policy, controller **602** may generate a new firewall policy. In some examples, the new firewall policy is configured to cause the at least one network interface card to at least one of drop the egress connection or block further egress connections from the application service.

The techniques described herein may be implemented in hardware, software, firmware, or any combination thereof.

Various features described as modules, units or components may be implemented together in an integrated logic device or separately as discrete but interoperable logic devices or other hardware devices. In some cases, various features of electronic circuitry may be implemented as one or more integrated circuit devices, such as an integrated circuit chip or chipset.

If implemented in hardware, this disclosure may be directed to an apparatus such as a processor or an integrated circuit device, such as an integrated circuit chip or chipset. Alternatively or additionally, if implemented in software or firmware, the techniques may be realized at least in part by a computer-readable data storage medium comprising instructions that, when executed, cause a processor to perform one or more of the methods described above. For example, the computer-readable data storage medium may store such instructions for execution by a processor.

A computer-readable medium may form part of a computer program product, which may include packaging materials. A computer-readable medium may comprise a computer data storage medium such as random access memory (RAM), read-only memory (ROM), non-volatile random access memory (NVRAM), electrically erasable programmable read-only memory (EEPROM), Flash memory, magnetic or optical data storage media, and the like. In some examples, an article of manufacture may comprise one or more computer-readable storage media.

In some examples, the computer-readable storage media may comprise non-transitory media. The term "non-transitory" may indicate that the storage medium is not embodied in a carrier wave or a propagated signal. In certain examples, a non-transitory storage medium may store data that can, over time, change (e.g., in RAM or cache).

The code or instructions may be software and/or firmware executed by processing circuitry including one or more processors, such as one or more digital signal processors (DSPs), general purpose microprocessors, application-specific integrated circuits (ASICs), field-programmable gate arrays (FPGAs), or other equivalent integrated or discrete logic circuitry. Accordingly, the term "processor," as used herein may refer to any of the foregoing structure or any other structure suitable for implementation of the techniques described herein. In addition, in some aspects, functionality described in this disclosure may be provided within software modules or hardware modules.

What is claimed is:

1. A network system comprising:
processing circuitry; and
one or more memories coupled to the processing circuitry and configured to store instructions which, when executed by the processing circuitry, cause the network system to:
obtain telemetry data;
determine, based on the telemetry data, that an application running on server processing circuitry does not meet at least one service level agreement (SLA) requirement, the server processing circuitry not including processing circuitry resident on a network interface card (NIC);
based on the application not meeting the at least one SLA requirement, determine to offload at least one component of the application from the server processing circuitry to the processing circuitry resident on the NIC;
obtain further telemetry data;
determine, based on the determination to offload the at least one component of the application from the server processing circuitry to the processing circuitry resident on the NIC and based on an analysis of the further telemetry data, that the application meets the at least one SLA requirement;
determine that a property of the application relating to the at least one SLA requirement meets a threshold; and
based on the property of the application meeting the threshold, determine to move the at least one component of the application from the processing circuitry resident on the NIC to the server processing circuitry.

2. The network system of claim **1**, wherein the at least one SLA requirement comprises at least one of a number of active connections, a network throughput, or a packet latency.

3. The network system of claim **1**, wherein the at least one component comprises a cryptographic function.

4. The network system of claim **1**, wherein the instructions further cause the network system to send a first notification indicative of the determination to offload the at least one component of the application from the server processing circuitry to the processing circuitry resident on the NIC to at least one of the server or a controller.

5. The network system of claim **4**, wherein the instructions further cause the network system to, responsive to the first notification, offload the at least one component of the application from the server processing circuitry to the processing circuitry resident on the NIC.

6. The network system of claim **1**, wherein the instructions further cause the network system to execute a machine learning model to determine the threshold.

7. The network system of claim **1**, wherein the property of the application comprises a number of drops in a predetermined period of time or a ratio of drops to active connections or sessions during a predetermined period of time.

8. The network system of claim **1**, wherein the instructions further cause the network system to send a second notification indicative of the determination to move the at least one component of the application from the processing circuitry resident on the NIC to the server processing circuitry to at least one of the server or a controller.

9. The network system of claim **8**, wherein the instructions further cause the network system to, responsive to the second notification, move the at least one component of the application from the processing circuitry resident on the NIC to the server processing circuitry.

10. A method comprising:
obtaining telemetry data;
determining, based the telemetry data, that an application running on server processing circuitry does not meet at least one service level agreement (SLA) requirement, the server processing circuitry not including processing circuitry resident on a network interface card (NIC);
based on the application not meeting the at least one SLA requirement, determining to offload at least one component of the application from the server processing circuitry to the processing circuitry resident on the NIC;
obtain further telemetry data;
determining, based on the determination to offload the at least one component of the application from the server processing circuitry to the processing circuitry resident on the NIC and based on an analysis of the further telemetry data, that the application meets the at least one SLA requirement;

determining that a property of the application relating to the at least one SLA requirement meets a threshold; and

based on the property of the application meeting the threshold, determining to move the at least one component of the application from the processing circuitry resident on the NIC to the server processing circuitry.

11. The method of claim **10**, wherein the at least one SLA requirement comprises at least one of a number of active connections, a network throughput, or a packet latency.

12. The method of claim **10**, wherein the at least one component comprises a cryptographic function.

13. The method of claim **10**, further comprising sending a first notification indicative of the determination to offload the at least one component of the application from the server processing circuitry to the processing circuitry resident on the NIC to at least one of the server or a controller.

14. The method of claim **13**, further comprising, responsive to the first notification, offloading the at least one component of the application from the server processing circuitry to the processing circuitry resident on the NIC.

15. The method of claim **10**, further comprising executing a machine learning model to determine the threshold.

16. The method of claim **10**, further comprising sending a second notification indicative of the determination to move the at least one component of the application from the processing circuitry resident on the NIC to the server processing circuitry to at least one of the server or a controller.

17. The method of claim **16**, further comprising, responsive to the second notification, moving the at least one component of the application from the processing circuitry resident on the NIC to the server processing circuitry.

18. Non-transitory computer-readable storage media storing instructions, which, when executed, cause processing circuitry to:

obtain telemetry data;

determine, based on the telemetry data, that an application running on server processing circuitry does not meet at least one service level agreement (SLA) requirement, the server processing circuitry not including processing circuitry resident on a network interface card (NIC);

based on the application not meeting the at least one SLA requirement, determine to offload at least one component of the application from the server processing circuitry to the processing circuitry resident on the NIC;

obtain further telemetry data;

determine, based on the determination to offload the at least one component of the application from the server processing circuitry to the processing circuitry resident on the NIC and based on an analysis of the further telemetry data, that the application meets the at least one SLA requirement;

determine that a property of the application relating to the at least one SLA requirement meets a threshold; and

based on the property of the application meeting the threshold, determine to move the at least one component of the application from the processing circuitry resident on the NIC to the server processing circuitry.

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